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[*Continued on page (III) of Cover.*

# DISCUSSION ON "NON-DESTRUCTIVE TESTING"

ARRANGED BY

THE JOINT COMMITTEE ON MATERIALS AND THEIR TESTING

AND HELD UNDER THE AUSPICES OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

25TH NOVEMBER, 1938, 10 A.M.–1 P.M. AND 2 P.M.–5 P.M.

WITH THE FOLLOWING INTRODUCTORY PAPERS:—

# PROCEEDINGS AT THE MEETING

The chair was taken at 10 a.m. by **Dr. A. P. M. Fleming, C.B.E., D.Eng., M.Sc.,** President of The Institution, supported by Dr. H. J. Gough, Chairman of the Joint Committee.

The President, on taking the chair, welcomed the foreign visitors and then called upon Dr. Gough to describe the objects of the Joint Committee.

**Dr. H. J. Gough:** Briefly, the Joint Committee, which has been in existence for one year, consists of one representative of each of 26 major technical institutions in this country. Its main objects are threefold: (1) To promote joint discussions on the wider aspects of the subjects of materials and their testing; (2) to assist a co-operating Institution or Society in the presentation of a paper, or group of papers, dealing with a more detailed aspect of one of those subjects; and (3) to undertake those duties with regard to international matters which properly devolve on the Joint Committee in accordance with its terms of reference. The Committee arranged a very successful discussion in Manchester last year on Notched Bar Testing; it is proposed to carry on the procedure then adopted, namely, to obtain as a basis of discussion a series of papers which represent the current views and opinions of experts not only of this country but of other countries abroad. The subject for discussion to-day is Non-destructive Testing, and we have obtained papers from Great Britain, Germany, Holland, and the United States of America. In connection with the papers from America, the Committee has had the fullest co-operation from the American Society for Testing Materials, which is the authoritative body in the United States for dealing with all questions relating to materials. We asked the American Society to arrange for us the actual papers and to select the authors, and they at once responded in a most helpful manner. As a result, we have a combined paper by three authors which represents most authoritative views. The Joint Committee will greatly welcome suggestions for subjects for future discussions, and I know that my colleagues on the Committee would like me to place on record how much we appreciate the fact that The Institution of Electrical Engineers is acting as host upon this occasion and the very considerable trouble taken in arranging this most important meeting.

**The President** then called upon the following authors in turn to deliver in abstract form their papers on the subjects indicated:—

*Magnetic and Electrical Methods.*

A. P. M. Fleming, C.B.E., D.Eng., M.Sc., and B. G. Churcher: "The Non-destructive Testing of Materials by Electrical and Magnetic Methods" (see page 519) (presented by Mr. Churcher).

Dr. R. Berthold (Germany): "Non-destructive Testing, based on Magnetic and Electrical Principles" (see page 529).

*X-Rays and Gamma-Rays.*

V. E. Pullin, C.B.E.: "Radiography—an Aspect of Non-destructive Testing" (see page 535).

Ir. J. E. de Graaf (Holland): "Industrial Radiography on the Continent of Europe" (see page 545).

*Acoustic and General Methods.*

S. F. Dorey, D.Sc.: "Acoustic and General Methods of Non-destructive Testing" (see page 552). In Dr. Dorey's absence, the summary of his paper was read by Mr. G. H. Ford, Secretary of the Joint Committee.

F. Förster, Dr. Phil., and Prof. W. Köster, Dr. Phil. (Germany): "Modulus of Elasticity and Damping in relation to the State of the Material" (see page 558) (presented by Dr. Förster).

*American Practice.*

A paper entitled "Non-destructive Testing in the U.S.A." (see page 565), prepared by a Committee consisting of Messrs. H. H. Lester, R. L. Sanford, and N. L. Mochel, of the American Society for Testing Materials, and giving the experience and views of the United States of America, was taken as read.

The papers by Dr. Berthold and Drs. Förster and Köster having been presented in German, brief summaries of the respective authors' remarks were given in English by Ir. J. E. de Graaf.

The President informed the meeting that there would be separate discussions on each of the three subjects on which the papers had been presented, and the discussion (see page 580) then took place on the first group of papers.

The meeting adjourned at 1.10 p.m. and, on resumption at 2 p.m., in the unavoidable absence of the President, the chair was taken by **Prof. W. M. Thornton, O.B.E., D.Sc., D.Eng.,** Past-President.

The discussion then followed on the second and third groups of papers.

A vote of thanks to the respective authors for their papers was proposed by **Sir William Larke,** seconded by **Dr. E. H. Rayner,** and carried with acclamation.

A special vote of thanks was also accorded, on the motion of the Chairman, to Ir. de Graaf for his valuable services as translator, on behalf of the German authors, throughout the proceedings of the meeting.

In the absence of Dr. Gough (Chairman of the Joint Committee) **Prof. Thornton** expressed on his behalf the cordial thanks of the Joint Committee to The Institution for having held the meeting under its auspices.

The meeting terminated at 4.30 p.m.

# THE NON-DESTRUCTIVE TESTING OF MATERIALS BY ELECTRICAL AND MAGNETIC METHODS

By A. P. M. FLEMING, C.B.E., D.Eng., M.Sc., President, and B. G. CHURCHER, Member.*

(*Paper received* 18*th August, and read at a meeting arranged by the* JOINT COMMITTEE ON MATERIALS AND THEIR TESTING, 25*th November*, 1938.)

## INTRODUCTION

Modern physics has arrived at the conclusion that fundamentally all matter and all physical phenomena are electrical manifestations. Indeed, the close connection between electrical and other forms of energy, such as magnetic and thermal energy, has so long been a matter of common experience that the utilization, in the non-destructive testing of materials, of what may broadly be termed electrical and magnetic methods is natural. The practical development of such methods has, however, been mainly due to the very specific, exact, and convenient manner in which electrical quantities, and hence those derivable from them, can be controlled, the enormous range over which they can be varied, and the precision with which they can be measured. Control at a distance and the production of very rapidly varying quantities may, in certain instances, be valuable properties.

It is well at the outset to define what we include under the term " electrical and magnetic methods." First must be included (A) those methods devised for the assessment of an intrinsically electrical or magnetic property of a material. Next (B), methods for the assessment or detection of a non-electrical or non-magnetic property or condition by means of electrical or magnetic effects in a material. We may envisage a third class (C) of methods in which electricity or magnetism is used indirectly or incidentally in the assessment of a non-electrical or non-magnetic property. In some instances in this very broad class the use of electricity or magnetism confers a decisive superiority over other possible methods, whereas in other instances the advantage is less marked, affording some minor convenience only. From a technical standpoint such methods are not in the same category as the first two, and space will not permit of more than a mention of a few of the more notable instances. Electrical and magnetic methods are widely employed in the measurement of dimensions, displacement, velocity, acceleration, fluid flow, pressure, temperature, illumination, and other quantities, but, not being methods of testing materials, are beyond the scope of the paper.

Fig. 1 shows how electrical and magnetic phenomena are utilized in the non-destructive testing of materials and illustrates the wide scope of the subject.

## ELECTRICAL PROPERTIES OF MATERIALS

### Resistivity

Proceeding according to the table shown in Fig. 1, the methods for measuring the resistivities of metallic conductors and the appropriate precautions against various sources of error are well known and do not require specialized equipment. The resistance of the specimen may be measured with ample accuracy (e.g. 0·1 %) by bridge or potentiometer and resistance standard, according to its magnitude. The temperature of the specimen may be regulated and measured by simple means and, given sufficient temperature range, the temperature coefficient of resistance determined. In measuring the temperature coefficient of some high-resistance alloys, the precautions against error from thermo-electric effects require special care on account of the smallness of the temperature coefficient and the magnitude of the thermo-electric effect with other metals. For this purpose the authors have used a bridge network consisting entirely of the alloy under test, three arms being kept in an oil bath at constant temperature and the fourth placed in a separate oil bath, the temperature of which could be varied.

In recent years semi-conductors having non-linear current/voltage characteristics have been developed and have found a variety of applications. These materials follow a law of form $I = E^{\alpha}/K$, where $K$ is a constant and $\alpha$ may be of the order of 4. In testing such materials the main consideration is how far and under what conditions the current/voltage relation, or, what comes to the same thing, the voltage/resistivity relation, holds good, and simple routine methods of testing have been devised to enable the required data to be obtained in an expeditious manner. The current/voltage relation at high voltages may be obtained by observing those quantities oscillographically during the application of a voltage impulse.

In measuring the resistivity of electrolytes the use of alternating current is sometimes necessary in order to eliminate polarization effects. In one method the liquid is introduced into a tubular glass cell fitted with current and potential electrodes. The component of voltage-drop in phase with the current may be measured by means of an a.c. potentiometer, and the resistivity thereby obtained. With weak solutions having a high resistivity, polarization effects may be neglected, and convenient portable instruments embodying an ohmmeter and hand-driven generator are in use which enable resistivity values to be rapidly obtained by non-technical users.

The measurement of the resistivities of dielectrics up to $10^{14}$ ohms per cm. cube presents no special difficulty. The leakage current corresponding to a known applied p.d. is measured by means of a reflecting galvanometer, and surface leakage is eliminated by means of a Price guard-ring electrode system, a standard form of which has

* Metropolitan-Vickers Electrical Company, Ltd.

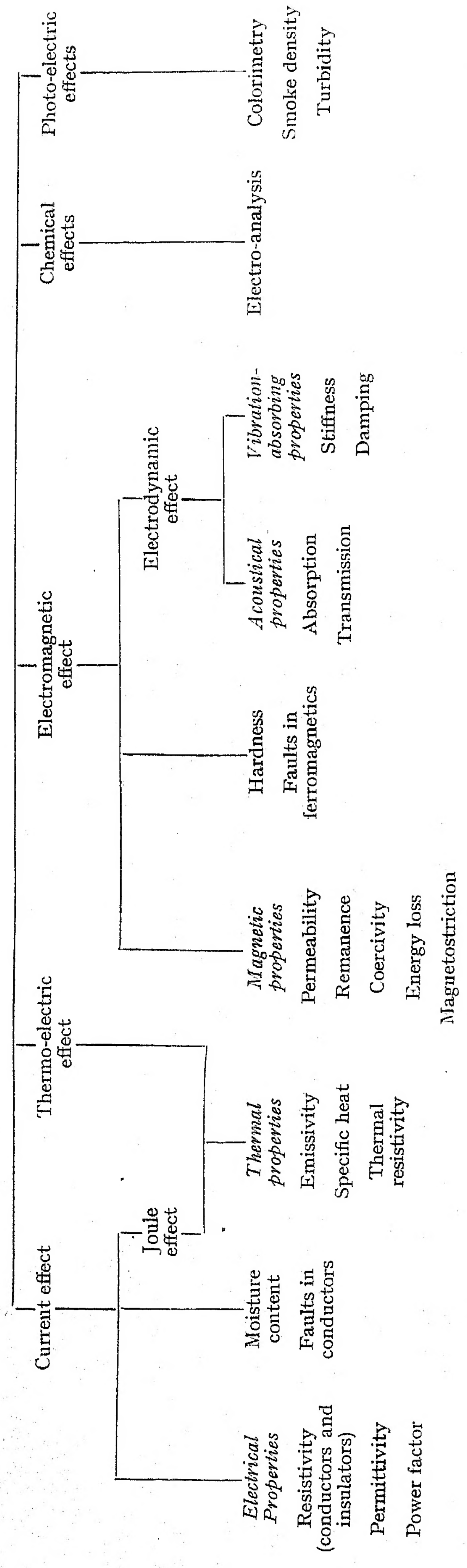



**Fig. 1.**—The utilization of electrical phenomena in the non-destructive testing of materials.

been recommended by the British Standards Institution.* Methods involving the rate of charge or discharge of a condenser have been devised for dielectrics of exceptionally high resistivity,† but their use is not generally necessary. A standard electrode arrangement has also been recommended by the B.S.I. for the measurement of the surface resistance of dielectrics under specified conditions of temperature and humidity.‡

### Permittivity and Power Factor

These two quantities form the key to the behaviour of a dielectric under alternating stress and are of particular interest in relation to non-destructive testing. Dealing first with the methods of determining power factor and permittivity, in principle the measurement consists simply in measuring the capacitance and power factor of a condenser composed of the specimen placed between suitable electrodes. For power and audio-frequency determinations the well-known Schering bridge, or some modification of it, is generally employed. Fig. 2

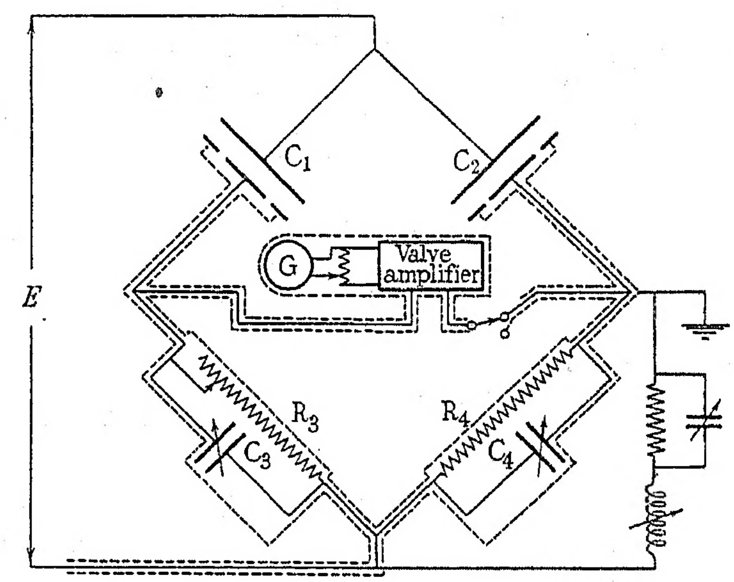



**Fig. 2.**—Diagram of Schering bridge.

shows diagrammatically a fully screened bridge arranged so that with the test condenser, say $C_2$, a guard electrode may be employed for eliminating surface leakage and capacitance. A Wagner earthing circuit, seen in the lower right-hand corner, is provided to enable the potential of the screens to be brought to equality with that of the conductors they enclose, thus eliminating screen capacitance effects. For testing materials of very low power factor, ample sensitivity is obtainable by means of an amplifier of moderate gain in the galvanometer circuit. There is no limit to the voltage at which such a bridge may be used, provided a suitable standard condenser $C_1$ is available. Fig. 3 shows a self-contained bridge with 40-kV compressed-gas sub-standard condenser.

The principal problem in power-factor and permittivity determinations is to obtain adequate contact between specimen and electrodes. An imperfect contact is equivalent to a condenser of unknown capacitance and power factor in series with the specimen, and the thinner the specimen the greater the uncertainty introduced. The most intimate contact is obtained with perfectly

* See Reference (1). † *Ibid.*, (2). ‡ *Ibid.*, (3).

clean mercury.* Fig. 4 shows a device, described by the British Electrical and Allied Industries Research Association, designed for use with mercury and provided with a guard electrode.† Almost as good contact is obtainable with colloidal carbon backed by a metal plate,‡ and provided the specimen is not porous this arrangement is particularly useful for temperatures above 100° C. and at power frequencies. For audio and radio frequencies the electrode resistance becomes excessive. Another method, now much used, is to apply thin tinfoil with a trace of vaseline as an adhesive. Contact can also be obtained by sputtering metal on to the specimen surface, but the process is slow and inconvenient and the results not specially good. In dealing with ceramics, metal-sprayed electrodes have been found very effective.

As the radio region of frequency is approached, bridge circuits become unsatisfactory owing to pronounced impurity in the constituent impedances, and a change in technique becomes necessary. The geometry of the circuit becomes of decisive importance, and that a measurement must not involve any appreciable change in it is an essential principle. Three methods have been developed. All involve adjustment of the circuit to resonance first with and then without the specimen inserted between the plates of a condenser forming part of the circuit, and all require the voltage induced in the circuit to remain constant and unaffected by such changes. In the " change of resistance " method, which has been used in this country for many years, the determination of the conductance and hence of the power factor of the specimen involves the insertion into the circuit of pure resistances of known value, and a limitation of the method is the difficulty of constructing such resistances for very high frequencies. For the highest frequencies this has led to the development of the " change of frequency " method, due to E. B. Moullin and developed by W. Jackson,* and the " change of reactance " method.† In both of these methods the power factor of the specimen is deduced from the form of a portion of the resonance curve, obtained by observing the voltage across the specimen when the circuit is detuned, in one method by varying by a small amount the frequency and in the other by varying the capacitance of a small vernier condenser connected in parallel with the specimen. The "change in reactance" method is generally regarded as the more convenient of the two and has been successfully used at frequencies up to 60 million cycles per sec. Fig. 5 shows an electrode arrangement for use with this method, incorporating the vernier condenser. Fig. 6 shows a complete equipment, which, to avoid body capacitance effects and interference from external sources, is completely screened by a metal cage. Arrangements are made for testing at temperatures up to 100° C. For higher frequencies still, a completely different technique seems called for, which, so far as the authors know, has not been fully worked out. Little standardization of permittivity and power-factor testing apparatus has taken place as yet in this country, but methods of testing

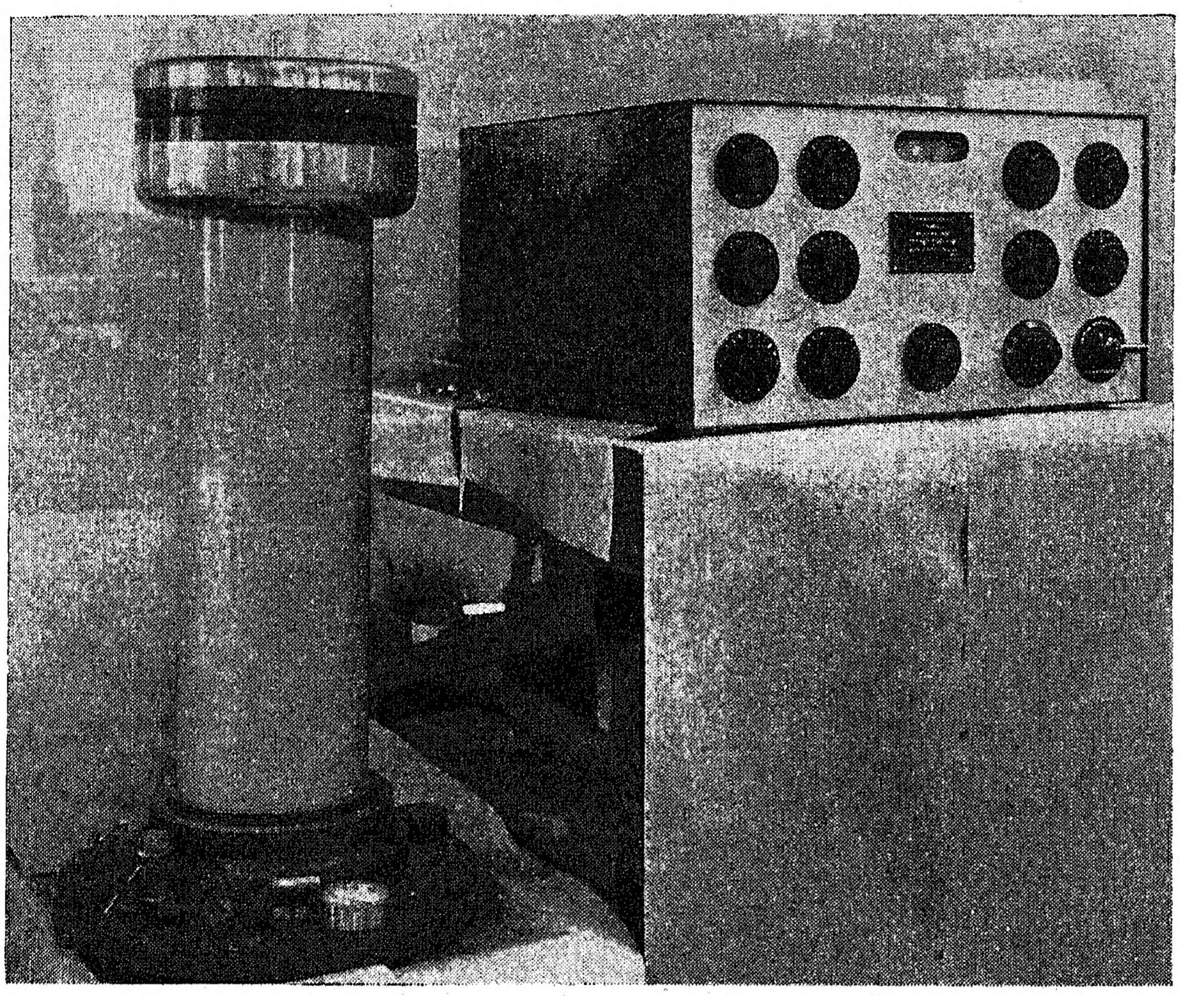


**Fig. 3.**—Schering bridge, with 40-kV standard condenser, for the measurement of energy loss in dielectrics.

* See Reference (4). † *Ibid.*, (5). ‡ *Ibid.*, (6).

* See Reference (7). † *Ibid.*, (8).

dielectrics are under examination by the Electrical Research Association in the course of an extensive research on dielectric phenomena.

In many dielectrics failure is due to thermal instability, a condition in which the rate of development of energy within the specimen exceeds the rate of dissipation. Now if the power factor and permittivity of a material are measured over a range of temperatures, the energy developed for a given electric stress, frequency, and temperature, may be computed. If the thermal-dissipation conditions are also known, the stress at which instability will occur may be deduced. Thus the ultimate failure of a dielectric may be predicted from data obtainable without destroying the specimen. This is, of course, an ideal principle, but, unfortunately, it is not universally applicable. With some dielectrics failure due to thermal instability occurs under certain conditions only, and with others under no condition of practical importance. For this reason puncture tests are still relied upon in practice.

Mention may be made at this point of some applications falling within Class B (see Introduction). Thus the moisture content of timber may be gauged from its resistance, and convenient practical methods have been developed for this purpose. A difficulty is the separation of surface from volume resistance. The change in capacitance with moisture content has also been utilized.* The change in power factor would appear to be an even more promising criterion, and surface effects could be easily eliminated. The present authors have found the change in power factor a sensitive index of the moisture content of papers. For research on laundry problems the "penetrability" of fabrics to different solutions is studied by observing at short intervals of time the electrical resistance of a membrane of the fabric.† Many attempts have been made to employ resistance methods for the detection of flaws in metals, but such methods have not come into general use. Owing to the low resistivity of metals, large currents are required to obtain sufficient sensitivity. Difficulties due to scale and surface irregularities also arise at the potential contacts.‡ For

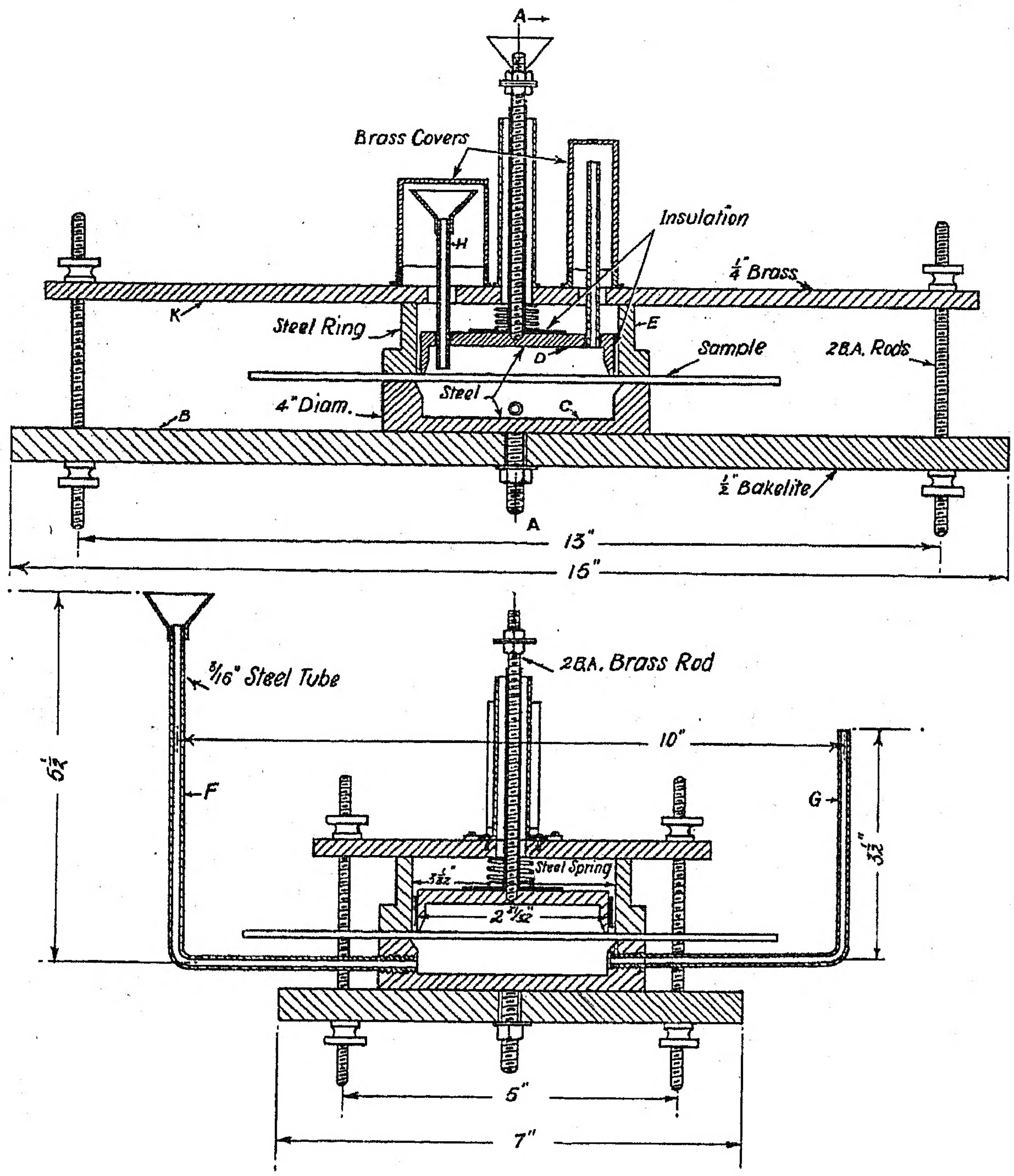



**Fig. 4.**—Mercury electrodes for the testing of dielectrics.

* See Reference (9). † *Ibid.*, (10). ‡ *Ibid.*, (11).

ferromagnetic materials the magnetic methods are much superior and will be discussed later.

### THERMAL PROPERTIES OF MATERIALS

The modern methods of measuring the thermal emissivity of surfaces, the specific heats of liquids and solids, and the thermal resistivity or conductivity of materials, are notable examples of the kind classified under C. The heat flow is set up, regulated, and measured electrically, and temperatures or temperature-differences are measured accurately by thermocouple. Space does not permit of a discussion of these methods, but it may be said that they are unsurpassed for precision and convenience.

### MAGNETIC PROPERTIES OF MATERIALS

The importance of ferromagnetic materials in the electrical industry needs no emphasis. The measurement of permeability, remanence, and coercivity, or the tracing of a complete hysteresis loop, all involve the correlation

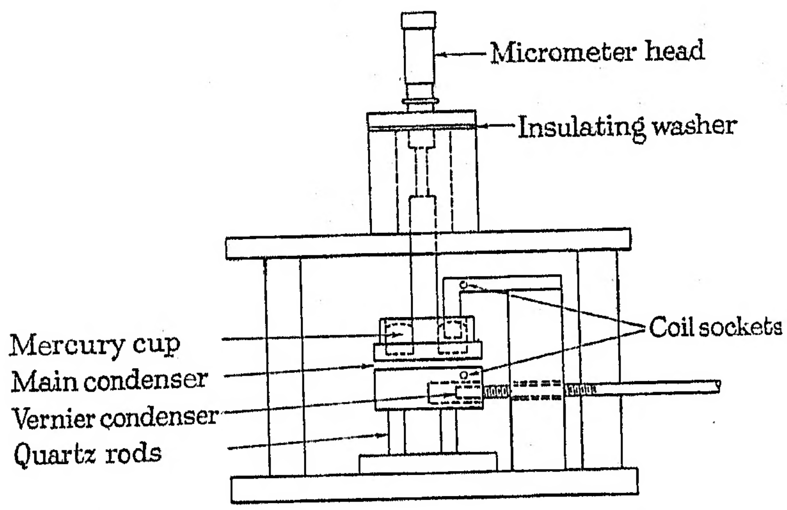



**Fig. 5.**—Electrodes for radio-frequency tests.

of the flux density ($B$) with the magnetizing field ($H$). A ring specimen, provided with a search coil for the ballistic measurement of $B$ and a suitable magnetizing winding, was originally employed and is still an ultimate standard of reference, but is now only used for special purposes owing to the development of methods which avoid the winding by hand of individual specimens and enable more intense magnetizing fields to be applied. Fig. 7 shows a modern permeameter suitable for testing both sheet and solid materials. In stating $B$ and $H$ values it is implied that the magnetization over the material part of the specimen is uniform. In this permeameter, means are provided for observing and adjusting the degree of uniformity of magnetization. With sheet materials a specimen of sufficient width (10 cm.) is used so that the edge-hardening effects of shearing the strips are small. $B$ is measured ballistically by a fixed search-coil wound on a former into which the specimen is inserted. In order to avoid large corrections at high magnetizations due to the inclusion within the search coil, of flux not contributed by the specimen, a compensating coil subjected to the same magnetizing field, of equal area-turns and connected in opposition to the search coil, is provided, so that the quantity ($B - H$) is actually measured by the deflections of the ballistic galvanometer, $B$ being obtained by adding $H$. $H$ is equal to the intensity of the field at the surface of the specimen and so is measured by thin search-coils wound on non-magnetic formers and placed close to the specimen surface. Similar coils located a short distance from the surface enable the perpendicular or radial rate of change of $H$ to be observed, this being the most sensitive criterion of the uniformity of magnetization of the specimen. By these methods the reluctance of yokes and joints is completely eliminated. This is of special importance with sheet materials, since constraint of the specimen by clamping must be avoided if reproducible data are to be obtained. The range of the instrument is from 0·1 to 2 500 $H$, the latter value being sufficient to

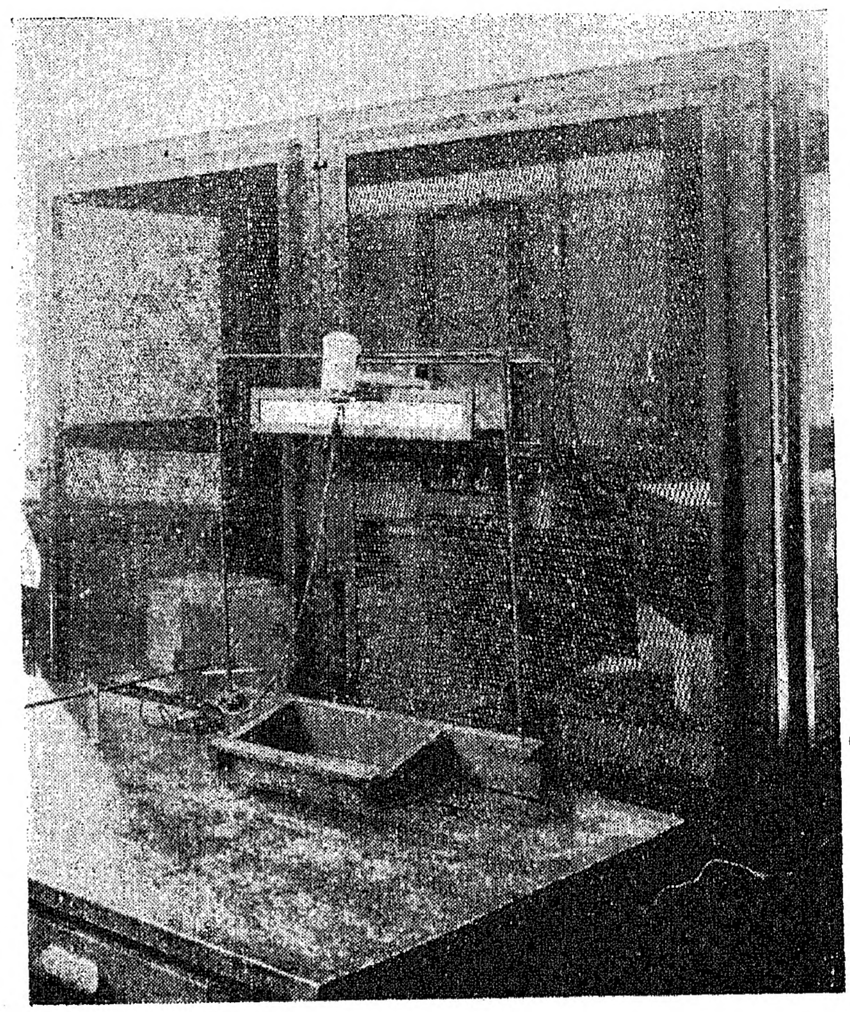


**Fig. 6.**—Equipment for the measurement of dielectric loss at radio frequency.

saturate all ordinary materials. An arrangement of rheostats and switches (shown on the extreme left of Fig. 8), operated in the appropriate sequence, enables remanence, coercivity, or a complete hysteresis loop, to be observed. Recommendations regarding permeability apparatus have been formulated.*

For the measurement of energy loss in sheet steels under alternating magnetization the Epstein apparatus† and the later Lloyd–Fisher apparatus,‡ both of American origin, have been used in this country. A disadvantage of the Epstein apparatus is the narrowness of the specimen (3 cm.), giving rise to serious error in tests on material as received from the steel maker, i.e. on unannealed specimens. To avoid this difficulty, one of the present authors devised an energy-loss apparatus§

* See Reference (12). † *Ibid.*, (13). ‡ *Ibid.*, (14). § *Ibid.*, (15.)

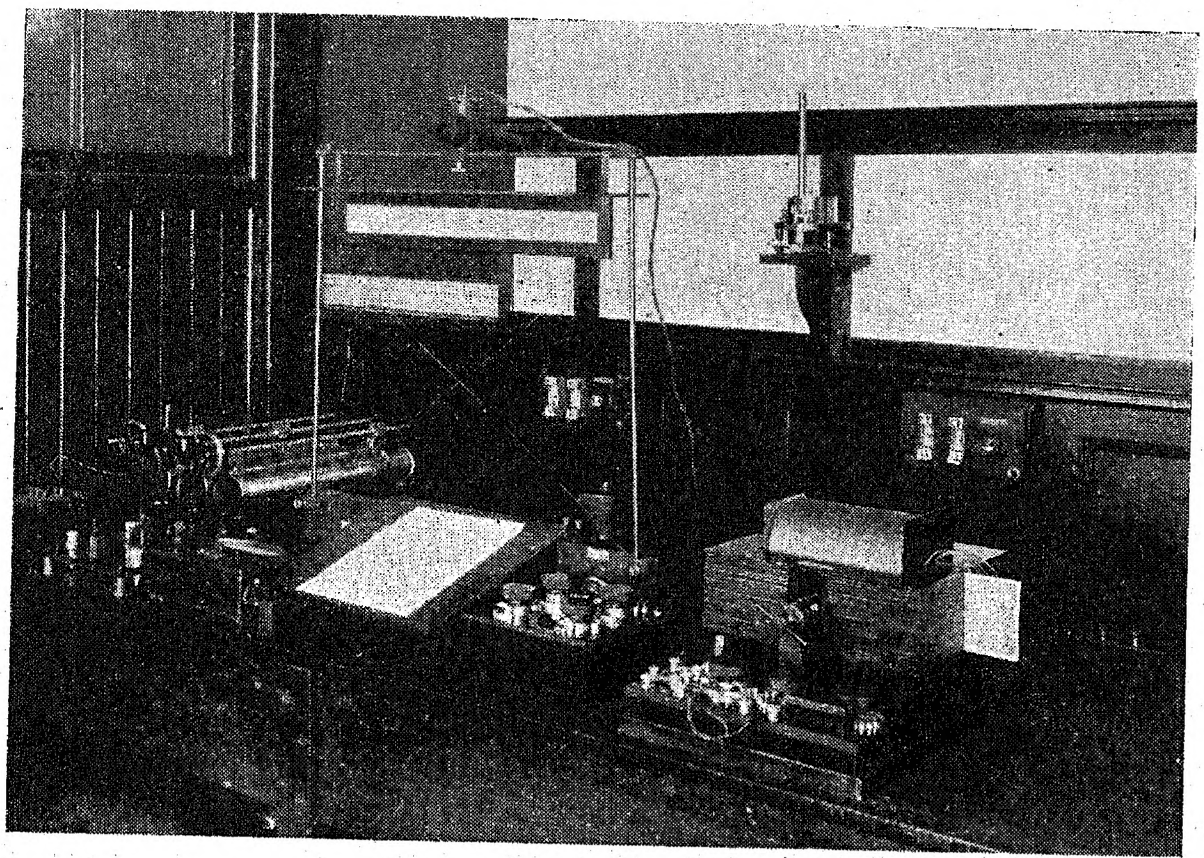


Fig. 7.—Permeability testing equipment.

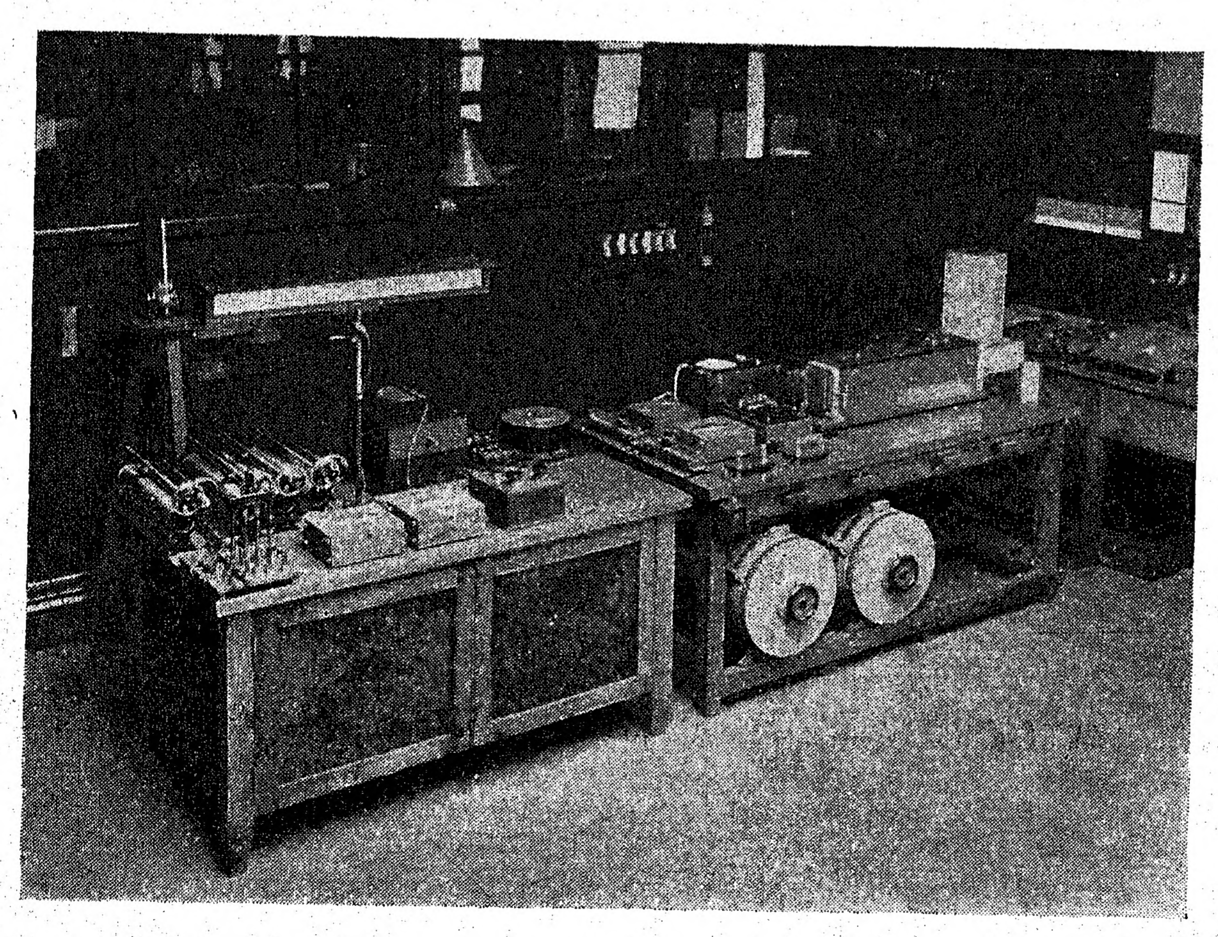
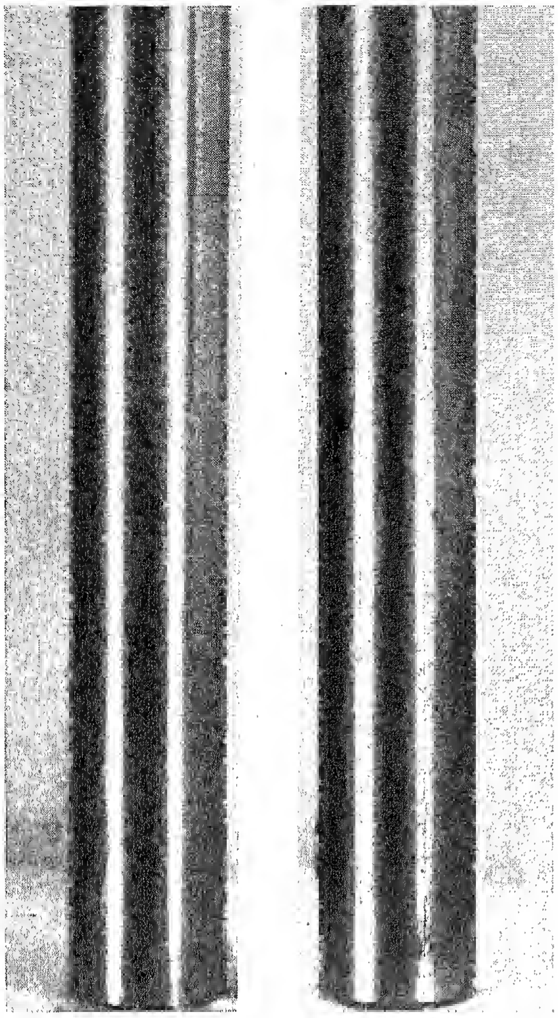


Fig. 8.—Permeability and energy-loss testing equipment.

*Plate 1*



(*a*) (*b*)

**Fig. 10.**—Magnetic crack detection. Bars (*a*) before and (*b*) after testing.

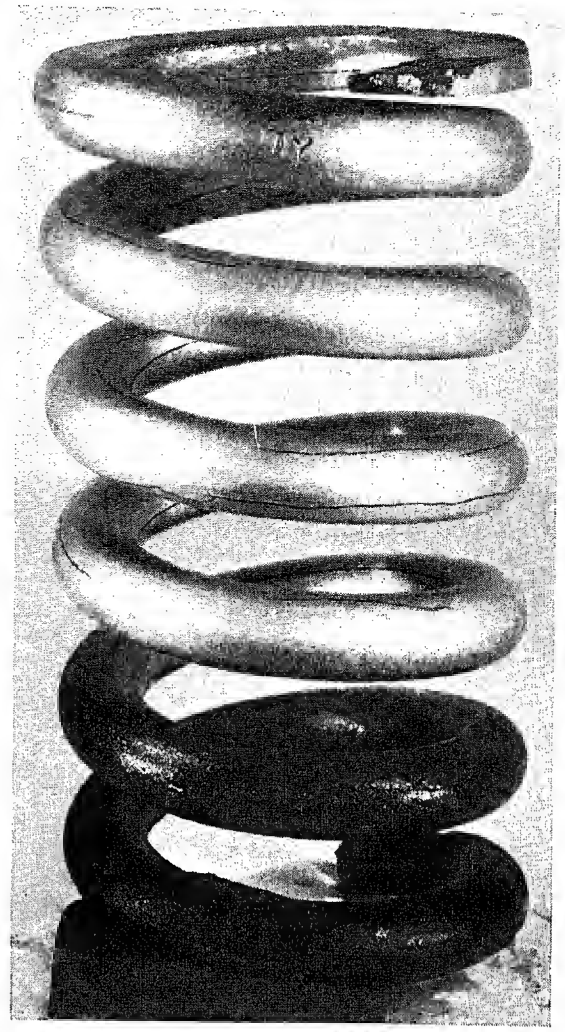


**Fig. 14.**—Magnetic crack detection. Spring after test.

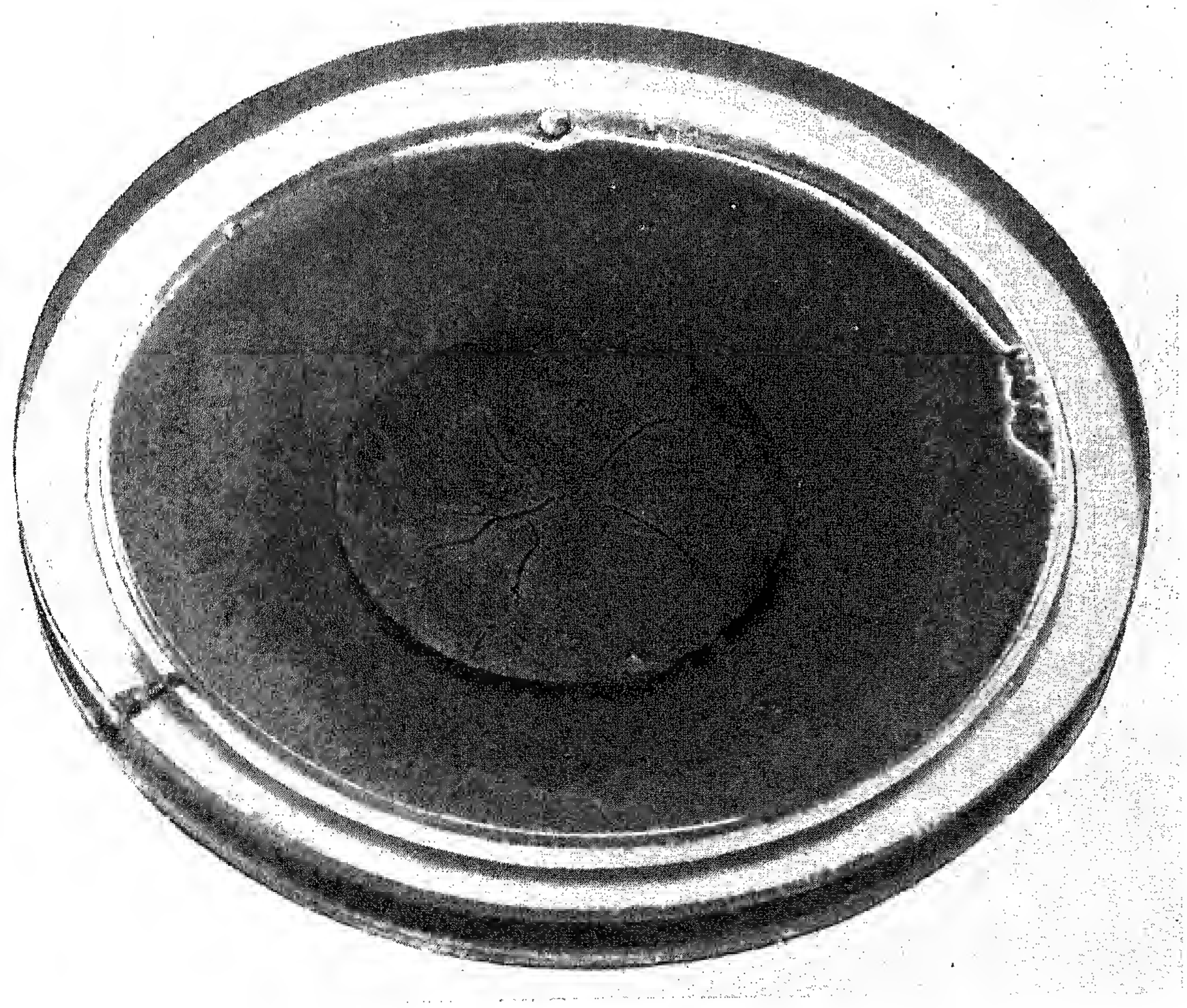


**Fig. 16.**—Portable transparent crack-detector. (The detector is shown placed over a section of bar material which had been previously magnetized circumferentially.)

(*Facing page* 524.)

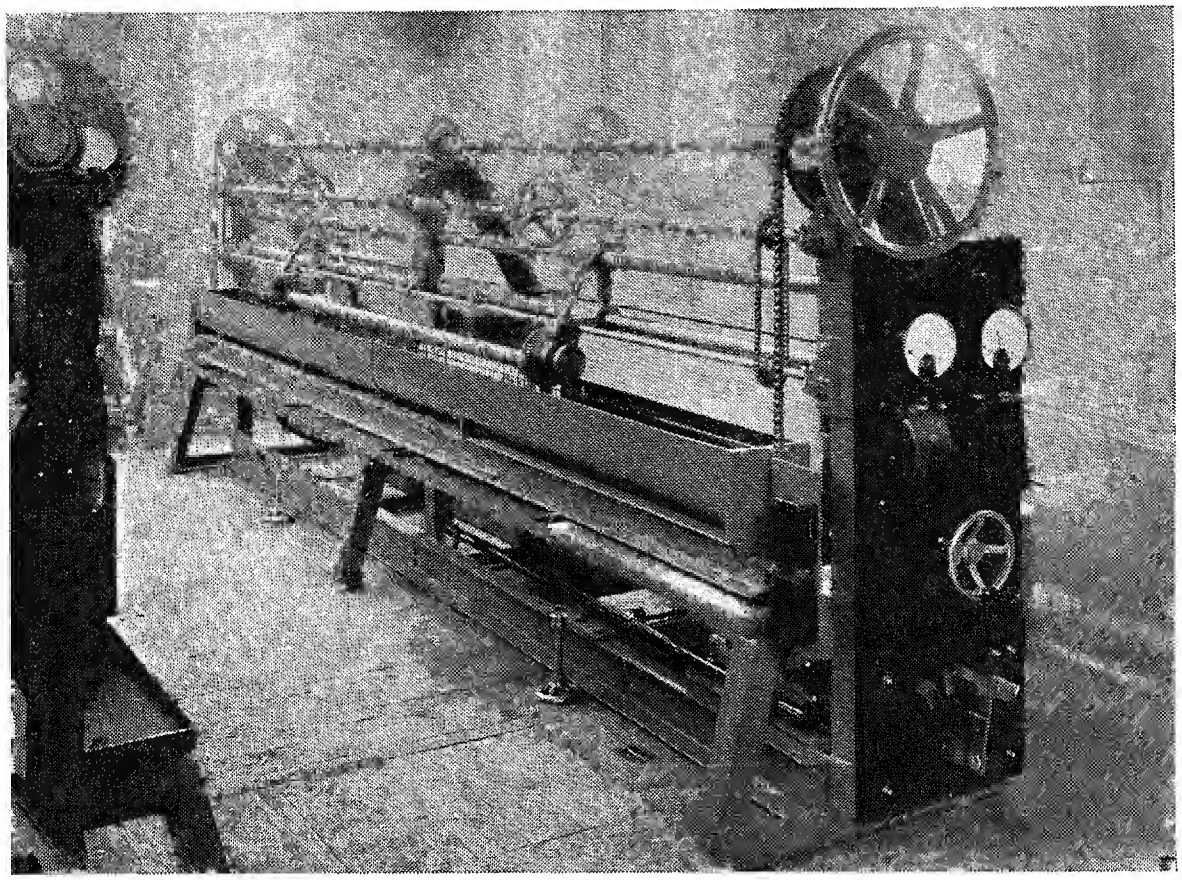


**Fig. 12.**—Magnetic crack-detection equipment for bar materials up to 12 ft. in length.

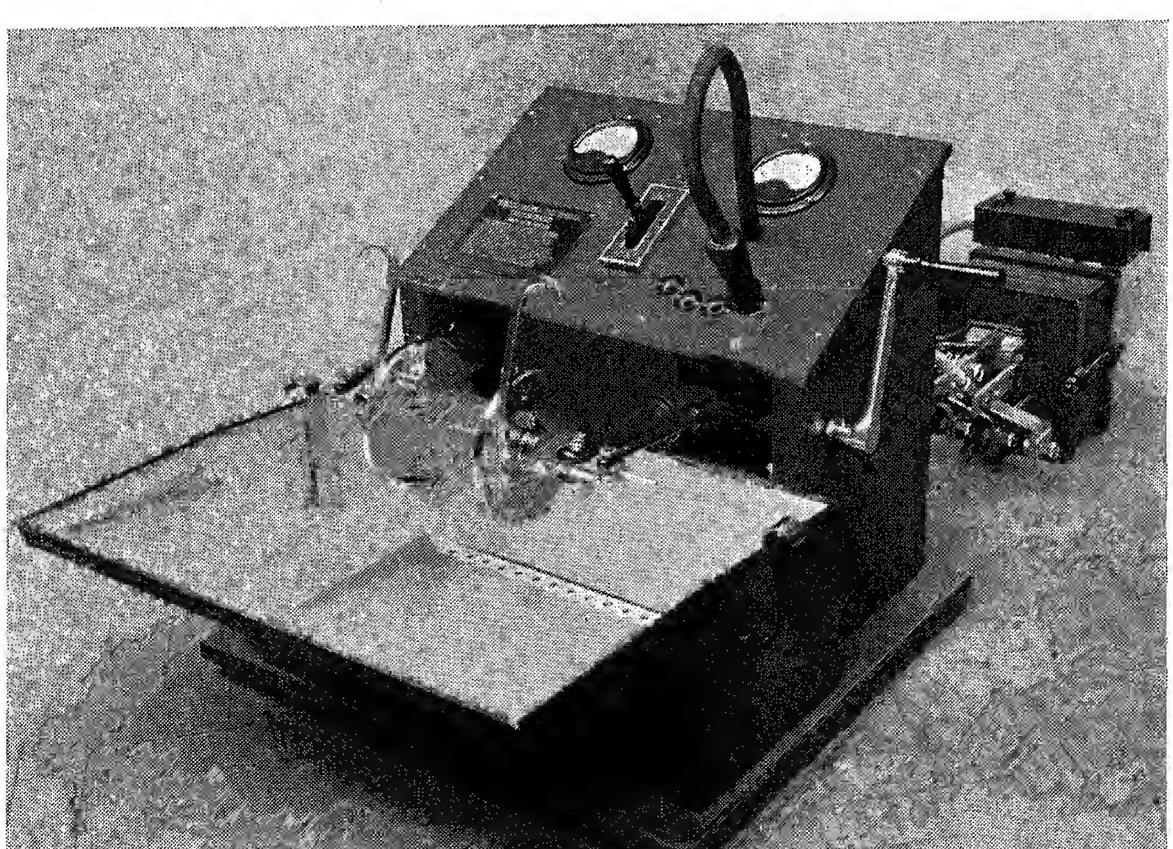


**Fig. 13.**—Magnetic crack-detection equipment utilizing superimposed continuous and alternating fields.

for 10-cm. wide specimens. One of these is seen on the right of Fig. 8, together with means for controlling and measuring the flux density ($B_{max.}$) in the specimen. For the latter purpose a voltmeter indicating mean volts is provided, in addition to an r.m.s. voltmeter, which enables the effect of wave-form distortion to be eliminated. The apparatus is capable of rapid and simple operation, a specimen consisting of 16 strips only.

The standardization of magnetic testing equipment has received consideration in this country, the British Standards Institution having formulated recommendations regarding apparatus for testing transformer sheet steel.* "Workshop" methods for testing permanent-magnet steel,† capable of an accuracy of ± 5 %, have also been standardized. In one of these the flux is measured by a pivoted moving coil carrying a known current and swinging in the field of the specimen under test. Another employs a rotating disc driven at a known speed in the field, the induced voltage giving a measure of the flux. These methods are useful where approximate values on large numbers of specimens are required.

The apparatus discussed so far is appropriate to the commercial acceptance testing of magnetic materials, where the specimens should be representative of fairly large quantities of material and where there are no severe limitations as to the permissible size of specimen. In research on magnetic materials small specimens are desirable, for several reasons. One apparatus‡ developed in this country enables a measurement of energy loss under alternating magnetization to be carried out on a single strip of steel 12 in. long and 4 in. wide. The effects of reluctance external to the specimen are eliminated by the use of search coils, the e.m.f.'s induced in which are measured by means of an a.c. potentiometer. A comparatively recent principle which has proved valuable in research is to observe the variations in torque acting on a small disc of the material as it is rotated through different angles in a magnetic field.§ According to the plane in which the disc is rotated the hysteresis loss associated with alternating or with rotational conditions of magnetization may be measured.‖ Fig. 9 shows an apparatus for this purpose. It can also be used for exploring the magnetic anisotropy of sheet materials, from which the orientation of the crystals constituting the specimen may be deduced.

Methods have also been developed for special materials or data that are not frequently required. Thus the iron-dust core materials used in radio apparatus are usually tested in toroidal form or whatever shape is to be used in practice, since the properties are dependent on geometrical considerations. Ring specimens are used for nickel-iron alloys or for testing at very low flux-densities. Methods have also been devised for measuring incremental permeability.¶

Magnetostriction, or the minute change in dimensions of a specimen when it is magnetized, is now recognized to be of fundamental importance in the study of magnetic materials. It is also the basic cause of the noise emitted by transformers and some other electrical apparatus. Apparatus employing a system of optical magnification has been developed by means of which a magnetostrictive change in length of a specimen of less than 1 part in 10 million can be detected.

## DETECTION OF FLAWS IN STEEL BY MAGNETIC METHODS

The detection in steel of faults which might cause mechanical weakness is an important example of non-destructive testing. It not only enables material to be classed as accepted or rejected, but also enables material of intermediate grade to be segregated and utilized for appropriate purposes. Further, the study of the faults disclosed may point the way towards their elimination.

The detection of faults, such as cracks, blowholes, or slag inclusions in iron or steel, by magnetic means depends upon the fact that the magnetic susceptibility of a fault is markedly inferior to that of the surrounding magnetic

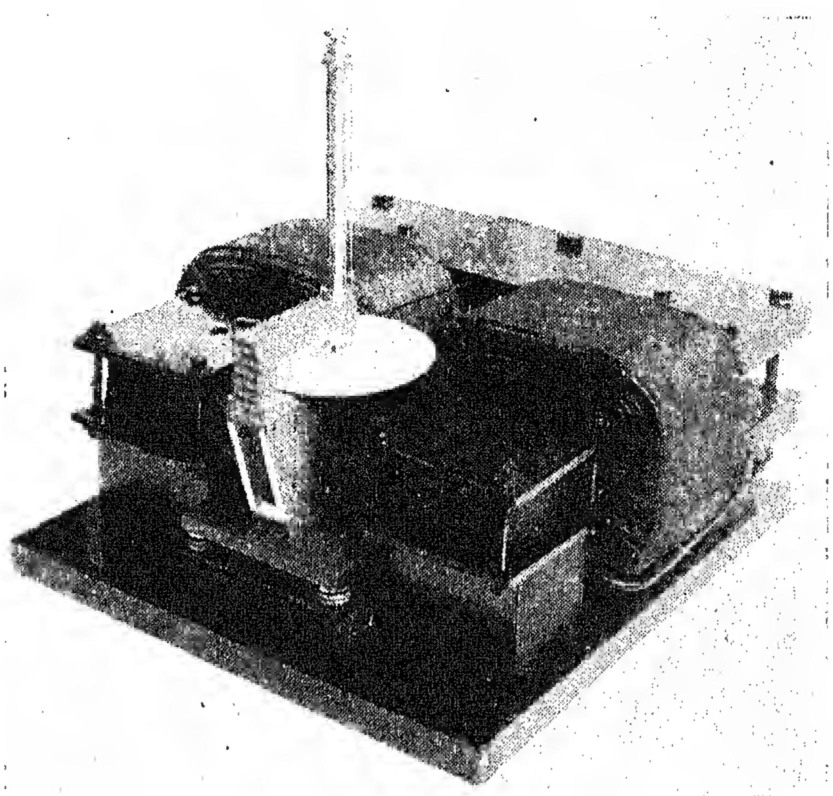


Fig. 9.—Torque magnetometer for magnetic measurements.

material of the specimen. The fault acts as a discontinuity or air-gap. The method consists essentially of setting up a magnetic flux in the specimen in such a way that the principal plane of the fault is substantially perpendicular to the direction of the flux. A fault lying across the path of the flux causes it to be diverted into the alternative path formed by the surrounding material. The distortion of the flux is not confined to the immediate vicinity of the fault but extends in a diminishing degree to a considerable distance all round the discontinuity and out through the surface into the surrounding air. It is this surface-field distortion which makes the method possible.

There are several methods of detecting the surface-field distortion. A very small pivoted bar magnet moved relative to the specimen will follow the variations in the surface field. Search-coil methods may be employed. These are of particular importance when deep-seated internal faults are under consideration. The more

* See Reference (12). † *Ibid.*, (16). ‡ *Ibid.*, (17).
§ *Ibid.*, (18). ‖ *Ibid.*, (19). ¶ *Ibid.*, (20).

common type of fault is the surface crack. Such cracks are sometimes so small or fine as to be passed over even when visual inspection is aided by a magnifying glass. As has been indicated, these cracks lying across the path of the flux produce surface flux distortion. This may be very local owing to the smallness of the fault, but it makes possible another method of detection. This is an adaptation of the well-known idea of using iron dust to delineate the form of a magnetic field. A crude form of the method is to lay a piece of white paper over the suspected region of the magnetized specimen and to sift on to it fine iron particles. If the paper is gently tapped, the particles tend to migrate to any point where the surface field is locally intense, i.e. where there is a crack, and to form a bridge across the crack, thus revealing its location. A better and more generally applicable method is to blow or sift iron dust directly on to the specimen. Cracks are then more readily revealed if the surface of the specimen is smooth. A still more effective method is to use very finely divided iron dust in suspension in paraffin or other suitable liquid.* This "magnetic fluid," as it has been called, may be sprayed or poured over the magnetized specimen, or the specimen may be immersed in it. The smoother the surface, the more clearly is a crack shown. In the case of black surfaces, a thin uniform coat of aluminium paint, which dries quickly, forms a very effective background. The methods adopted for magnetizing the specimen vary according to the plane of the most probable fault, convenience, and other factors. This point is better illustrated in the course of a review of the methods used for different types of material. It is advantageous to utilize the applied field rather than the remanent field, since with soft materials the latter may be inadequate.

The faults produced in rolling or drawing rods, tubes, or wires, are parallel to the axis. Hence circular magnetization is required. This may be effected by passing a current along the specimen. Fig. 10 (see Plate 1, facing page 524) shows a mild-steel bar before and after testing, the longitudinal faults being clearly visible. Fig. 11 shows an apparatus for bars up to 3 ft. in length. The level of the magnetic fluid in the tank is raised by compressed air while the alternating current flows through the bar. The fluid level is then lowered and the bar may be removed for inspection. The agitation of the iron particles by the alternating field is found to expedite the lining-up at the cracks.

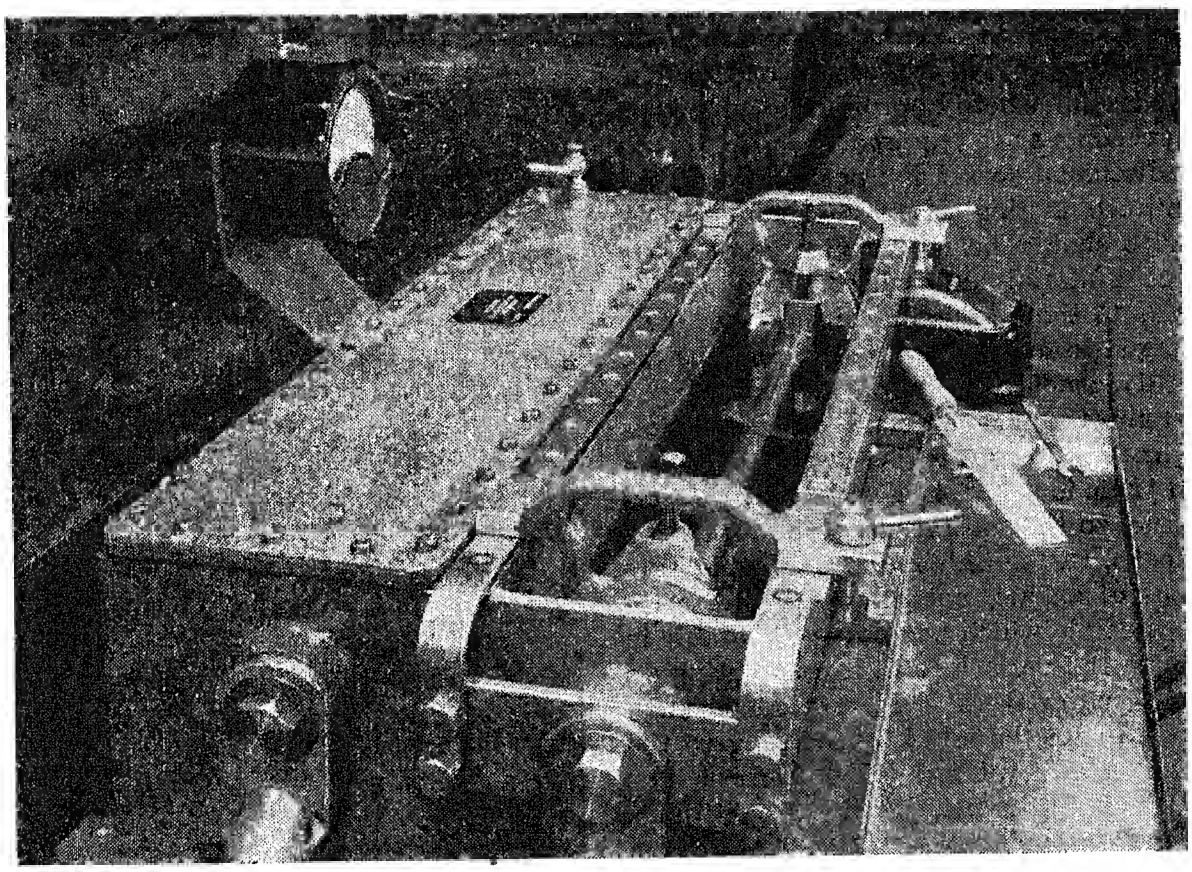


**Fig. 11.**—Magnetic crack-detection equipment for bar materials up to 3 ft. in length.

Fig. 12 (see Plate 2) shows an equipment for bars up to 12 ft. long and 3 in. diameter. In this case the specimen is flooded with magnetic fluid by a trough raised by suitable mechanism. In cases where flaws are likely to occur in more than one plane, two modes of magnetization may be used simultaneously. Thus a longitudinal continuous flux may be superimposed on a circular alternating flux, the result being a spiral magnetization which reverses with each alternation of the circular flux. Fig. 13 (see Plate 2) shows an apparatus embodying this principle. While springs must be regarded as products rather than materials, the faults of spring steel may only be fully developed after the spring has been wound. Fig. 14 (Plate 1) shows a spring after testing, aluminium paint having been previously applied to give a background; and Fig. 15 shows an equipment for testing aero-engine valve springs. A portable detector which may be conveniently applied to magnetized articles is shown in use in Fig. 16 (see Plate 1).

* See References (21) and (22).

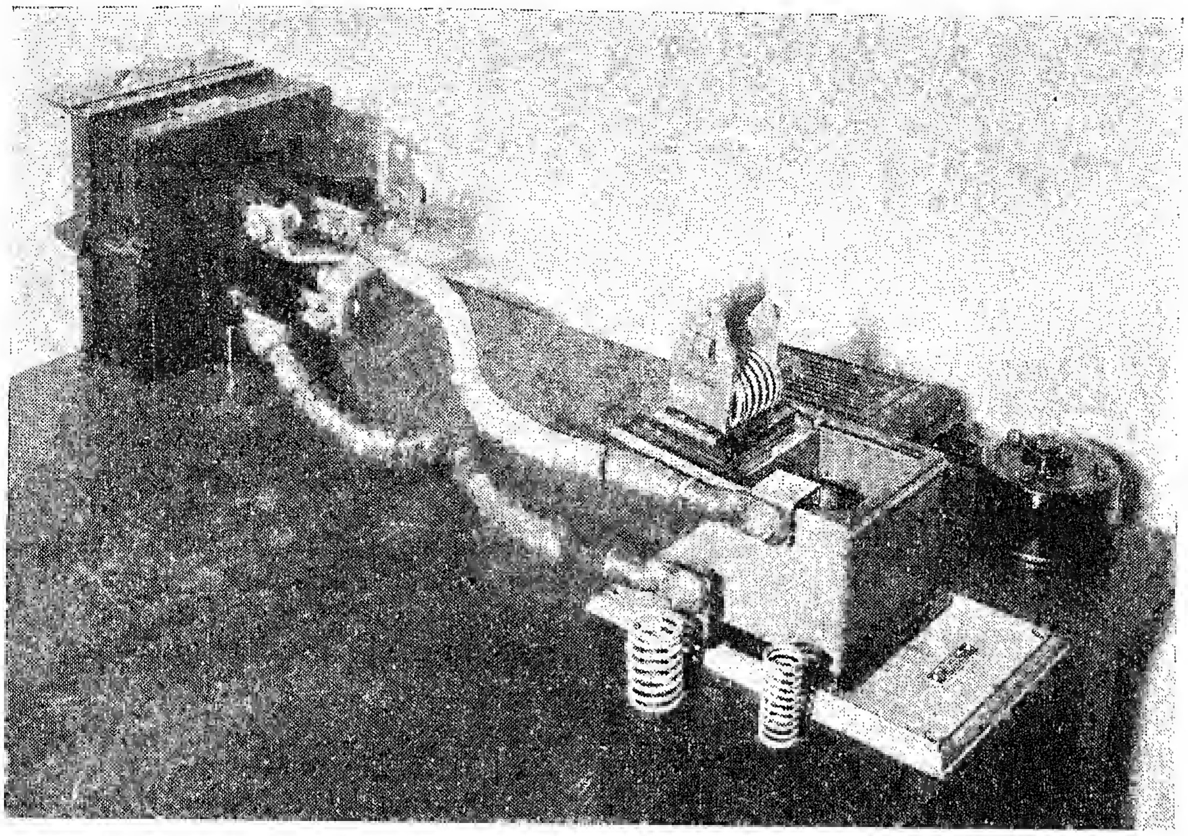


Fig. 15.—Magnetic crack-detection apparatus for small springs.

Many other applications of these so-called ferro-graphic methods have been made, particularly to manufactured products. An example is shown in Fig. 17. In the use of magnetic methods of flaw-detection, experience in the interpretation of the indications is of vital importance, as without it erroneous conclusions may be reached.

## METHODS OF TESTING METALLURGICAL CONDITIONS

Electromagnetic methods have been used to provide an index of the metallurgical condition of such materials as tool steel.* The specimen—a bar, for example—is placed within a solenoid carrying alternating current, and the components respectively in phase and in quadrature of the voltage induced in a search coil surrounding the specimen are measured. These quantities are then empirically co-ordinated with metallurgical factors, such as quenching temperature, drawing temperature, and quenching time. A differential apparatus has also been used, by means of which indications are obtained in terms of a standard specimen. These methods do not appear to have been adopted to any great extent in this country.

## ACOUSTICAL PROPERTI

The outstanding advances in the science of acoustics during the last decade would hardly have been possible without the electrical technique upon which the subject now rests. The measurement of the coefficients of sound transmission of walls or sheet materials and the measurement of the coefficients of absorption or reflection of sound-absorbing materials are important examples in Class C. These tests require the setting-up of pure tones of adjustable frequencies and intensities, and the measurement of acoustic pressures in free space. Owing to their superiority in respect of range, precision, and convenience, electrical methods are now used almost exclusively.

* See Reference (23).

Fig. 17.—Magnetic crack-detection equipment for small manufactured parts.

## VIBRATION-ATTENUATING PROPERTIES

Closely allied to acoustical properties are the vibration-attenuating properties of materials used for preventing the transmission of vibration (such as that from machinery) to buildings. The theoretical basis of the

application of such materials is now well understood, and predetermination of practical results for a given set of conditions is now possible if the properties of the material to be used are known.* It is now appreciated that data obtained under static conditions are inadequate, so methods for determining the dynamic stiffness and damping of resilient materials have been developed. Though the properties measured are mechanical, the technique is electrical. An example of an apparatus for such tests is shown in Fig. 18.

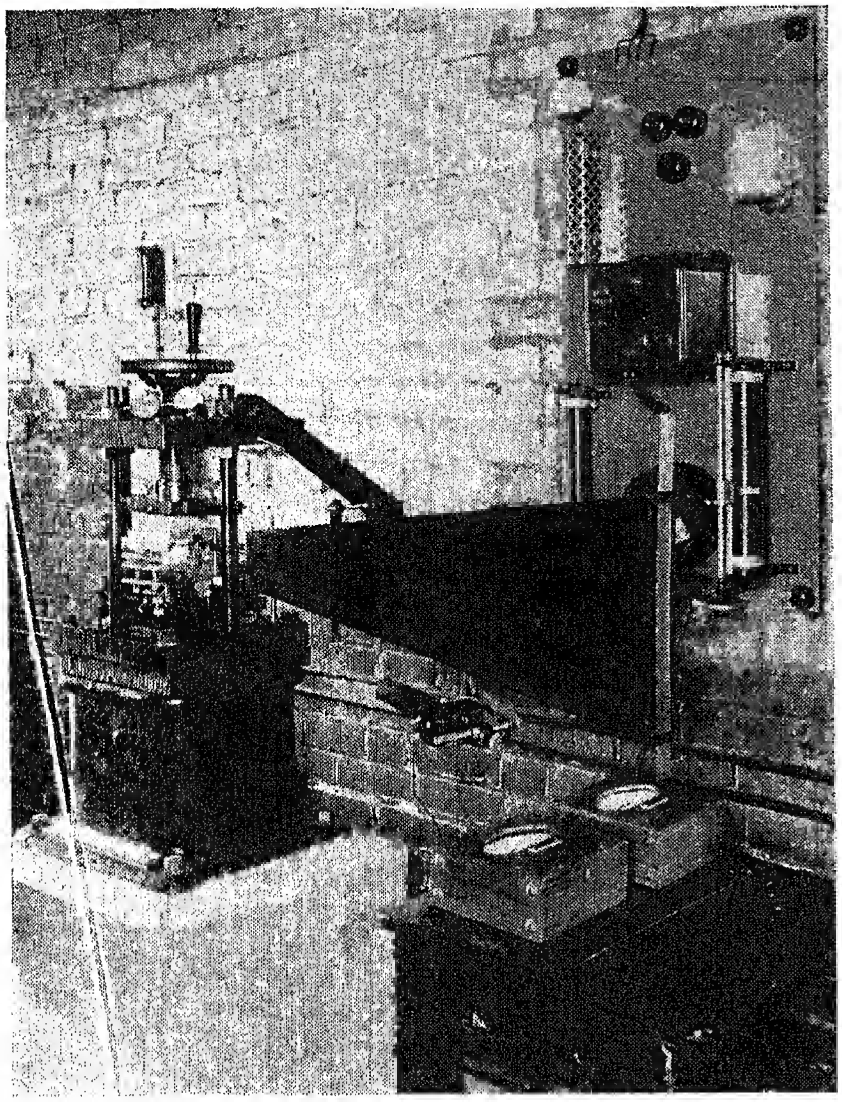


Fig. 18.—Apparatus for testing vibration-attenuating properties of materials.

## RADIATION AND ELECTROCHEMICAL TESTS

The various forms of radiation which may be set up electrically form a vast field of non-destructive testing. Some of them, particularly X-ray methods, are being discussed in another paper.† Then there are the numerous tests involving light, such as the testing of optical materials and reflecting surfaces, colour matching, the testing of smoke density and the turbidity of liquids, and many others. Fluorescence analysis by ultra-violet light is a large subject with a highly developed technique and has been applied in agriculture and to food products, papers, cellulose materials, and glass. These subjects are only indirectly related to the subject of the paper and are so extensive that no more than a reference to them can be made. There is also the important field of electrochemical tests. These could only be adequately reviewed in a separate paper.

* See Reference (24).
† J. E. de Graaf (see page 545).

## ACKNOWLEDGMENTS

The authors wish to record their indebtedness to the British Electrical and Allied Industries Research Association, the British Launderers' Research Association, the Equipment and Engineering Co., Ltd., and members of the staff of the Research Department of the Metropolitan-Vickers Electrical Co., Ltd., for information and assistance in the preparation of the paper.

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[The discussion on this paper will be found on page 580.]

# NON-DESTRUCTIVE TESTING, BASED ON MAGNETIC AND ELECTRICAL PRINCIPLES

By Dr. R. BERTHOLD.*

(*Paper received* 12*th September, and read at a meeting arranged by the* JOINT COMMITTEE ON MATERIALS AND THEIR TESTING, 25*th November*, 1938.)

## INTRODUCTION

Many attempts have been made, by constructing and applying magnetic and electrical testing devices, to bridge the gaps between and to overcome certain disadvantages of other non-destructive testing methods such as X-rays and radium (gamma radiation). The following notes show how far success in this direction has been attained on the Continent, and details of the latest developments are given. The author deals mainly with developments in Germany, as he knows these best. Those methods are dealt with which, generally speaking, have shown themselves to be most practicable; details of new methods and of special cases will be discussed later.

## (1) THE MAGNETIC-POWDER METHOD

The magnetic-powder (or filings) method shows up fine cracks, slag inclusions, and similar flaws, at, or close to, the surface of the specimens, which cannot be seen, even with a lens. The specimen is magnetized for this purpose and is then dusted with dry magnetic powder, or it is sprayed with oil containing suspended metal. The flaws are rendered visible by a heaping-up of the powder in that place. Apparently this method was first indicated by W. E. Hoke (American patent No. 1426384 of 1922). On the Continent, however, this method of testing has only been adopted during the last few years, but during this short period it has developed even more rapidly than radiography. This statement, however, principally applies to Germany and, to some extent, to Italy, whilst on the remainder of the Continent the number of magnetic testing plants in use in the year 1937 amounted at the most to 50, of which more than half were in France.

The great sensitivity of the method for the detection of flaws, close to the surface, and its failure when the flaws are deeply situated, may lead, when it is not properly applied, either to an over-enthusiastic adoption or to a premature condemnation of the method. In spite of the apparent simplicity of the non-destructive method by which flaws are detected by means of filings, its technical adoption does require a knowledge of its physical basis if it is to be utilized advantageously. For this reason a short summary of these physical characteristics may be useful.

### Physical Principles †

When magnetic lines of force pass through a magnetizable object they will be diverted in those places where there is a change in permeability. If the permeability is lower in the faulty area than in the sound area, part of the lines of force will pass through the air, over the flaw. The magnetic resistance, and in consequence the magnetic energy of the displaced field, are reduced by

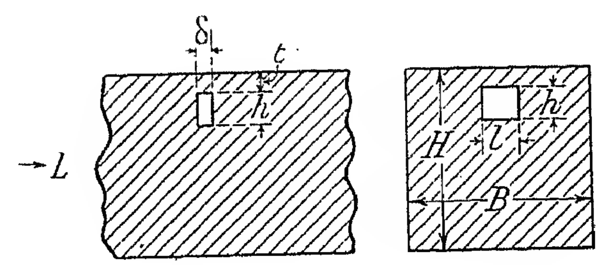



**Fig. 1.**—Description of the parameter in Figs. 2–4.

sprinkling iron filings on the dispersion path. This gain in energy, which is related to the unit length of the path, represents the force with which the filings are retained over the place where the flaw is located. Only when this force is greater than the mechanical forces which might cause the filings to be removed from that position (blowing, washing, gravity) is it possible to expect an indication of a flaw.

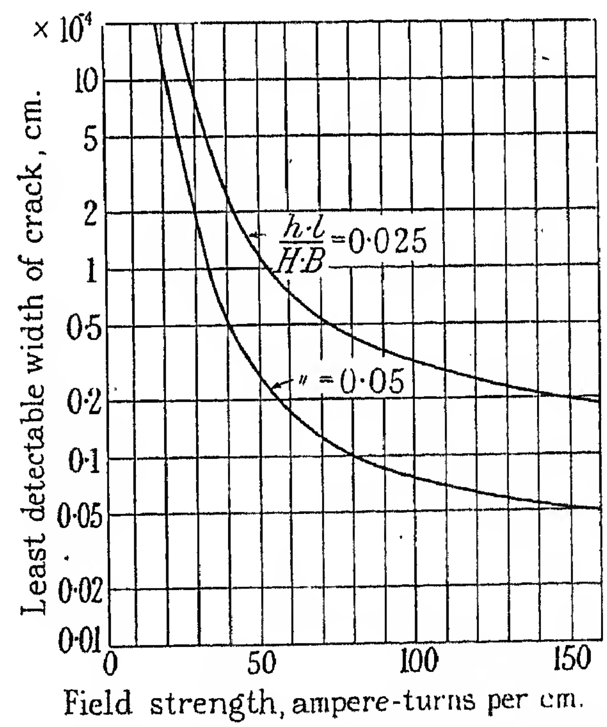



**Fig. 2.**—The maximum width of a flaw that can be indicated in relation to the field strength.

Effect for a flaw 2·5 to 5 % of the cross-section; crack situated at the surface; length of filings $5 \times 10^{-4}$ cm.

In view of this consideration there are numerous factors involved, particularly the relation between the field strength, the size, position, and direction of the flaw. The boundary curves shown in Figs. 2–4, which show the

* Reichs-Röntgenstelle, Berlin.
† Extensive particulars are given by R. BERTHOLD: "Atlas der zerstörungsfreien Prüfverfahren" (J. A. Barth, Leipzig, 1938).

possibilities of flaw indication, have been plotted taking into account the simplified assumptions that the flaw is a crack or a crevice perpendicular to the direction of the field and that the section of the specimen is uniformly penetrated by the lines of force.

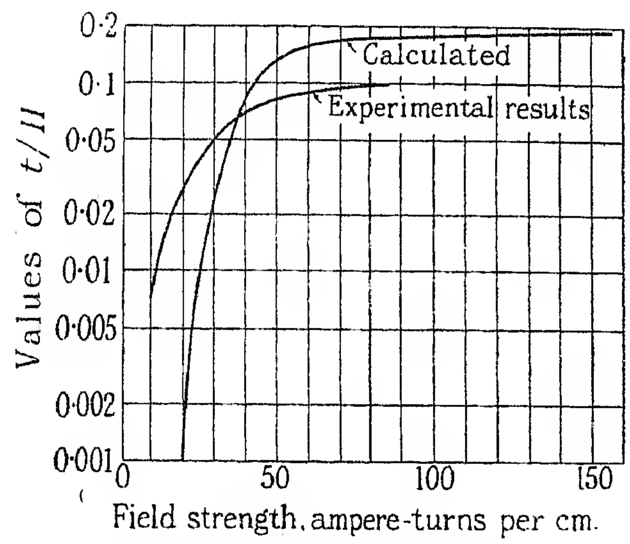



**Fig. 3.**—Depth effect of the magnetic-powder method in relation to the field strength.

Effect for $10^{-3}$ cm. width of crack; 5 % weakening of cross-section; $5 \times 10^{-4}$ cm length of filings.

Fig. 2 shows the extraordinary sensitivity of the method for the investigation of the finest cracks. This has been proved experimentally. This sensitivity decreases with field strengths below about 50 ampere-turns per cm. (A.T./cm.) and with field strengths exceeding 90 A.T./cm. it only increases slightly.

Although this method is so extremely sensitive for the detection of flaws at or near the surface of the object, the

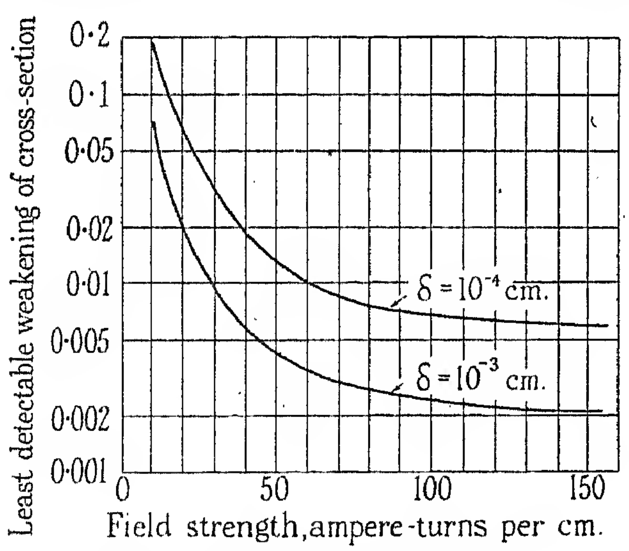



**Fig. 4.**—The least detectable weakening of the cross-section in relation to the field strength.

Effect for $10^{-3}$ and $10^{-4}$ cm. width of crack; crack located at the surface; $5 \times 10^{-4}$ cm. length of filings.

depth attained is very slight (see Fig. 3), and rapidly diminishes below 30 A.T./cm. Above 60 A.T./cm. it hardly increases.

Thus the most favourable field strengths are between 30 and 90 A.T./cm. Increasing the field strength above 90 A.T./cm., when using the normal mixture of magnetic powder and oil, results in the retention of the filings by the sound surface, as well as by the cracked surface. If this danger is avoided by using thin oil, then small, negligible flaws are exaggerated.

Fig. 4 shows the influence of the field strength on the reduction of the cross-section which can be detected. In this case, too, the most favourable field strengths are situated between 30 and 90 A.T./cm. With the practical application of the powder method of detecting flaws, extremely small cracks are frequently discovered; these have a less weakening effect on the transverse section than would be expected from Fig. 4. This occurs when the requirement regarding the uniform distribution of the field in the cross-section of the specimen has not been

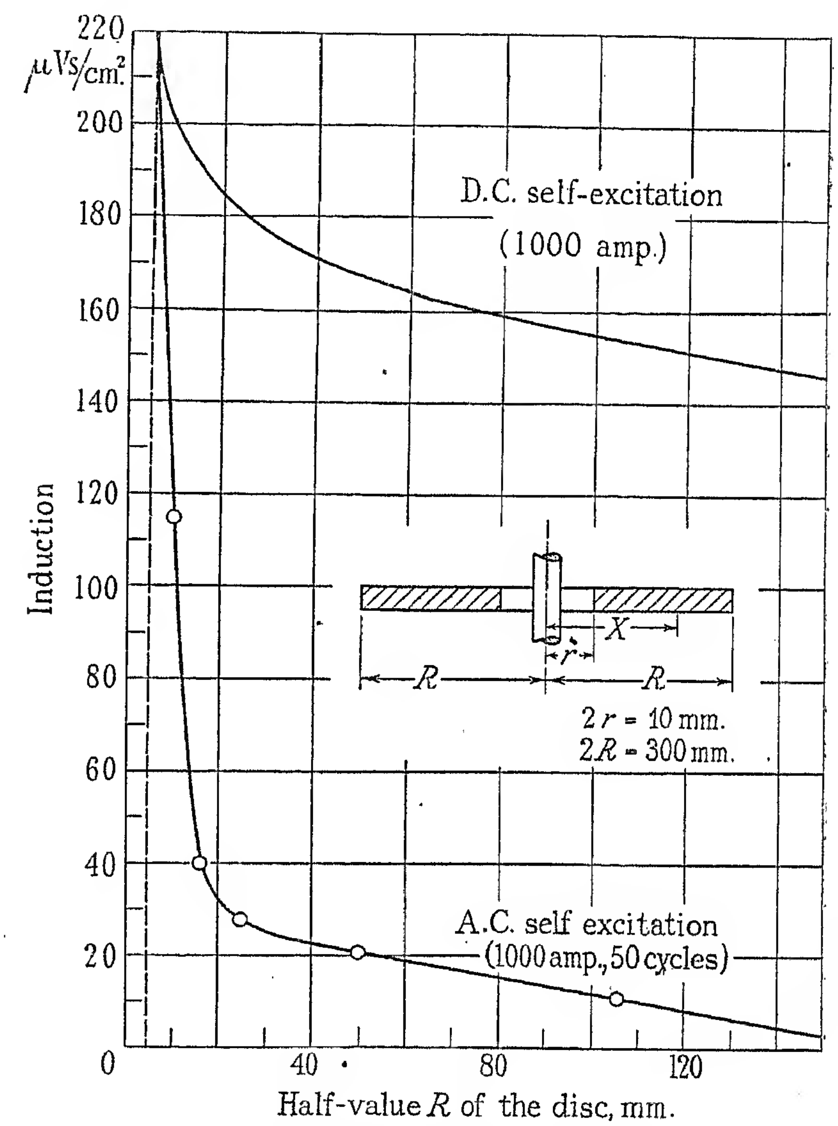



**Fig. 5.**—Course of the induction in a steel disc with direct and alternating current—self-excitation.

Effect for 1 000 amperes at 50 cycles per sec.

complied with. Actually, however, this requirement is only met by a specimen of uniform cross-section clamped between the pole-pieces of a d.c. electromagnet. With all other methods of field excitation, uneven field distribution will occur; this alters our view-point of the influence of the weakening of the section on the indication of the flaws.

### Excitation of the field

If a portable magnet be placed on the top surface of a large object having thick walls, the field strength in the region nearest to the magnet diminishes rapidly with the depth. A flaw in the surface having only a very slight effect on the section of the object will, however, exert a considerable influence on the magnetic flow, and it will thus be indicated more easily.

A non-uniform distribution of the magnetic field becomes important when the magnetic field is built up with the aid of a current flowing through the object. If the distribution of the induction in a steel disc provided with an opening in the centre is measured it will be seen that the induction in the side of the opening nearest to the lead supplying the current is by far the greatest (see Fig. 5). This occurs when direct current is employed, and is particularly strong when alternating current is passed through the central conductor. These ratios are the same in the case of a solid cylindrical object; in this case the greatest induction occurs at the surface of the specimen.

In accordance with these observations, the calculated influence of the percentage weakening of the cross-section varies with the indication sensitivity. At a first approximation it may be assumed that not the total cross-section but the magnetized cross-section of the object, and its percentage weakening, determine the error in the calculation.

If the depth at which the magnetic field amounts to even $1/e$* times the active field on the surface, is taken more or less at random as the penetration depth, it will be found to be about 5 to 10 mm. when 50-cycle alternating current is applied. This "penetration depth" represents a reduction in the thickness of the walls of the object when the influence of a weakening of the cross-section by a flaw is considered in the light of the sensitivity. From this it will be seen that by selecting the most suitable method of field excitation a real improvement of the sensitivity can be achieved.

This increase in the sensitivity for flaws in the cross-section of the object has, in the first place, a detrimental influence on the depth effect; it naturally decreases when the magnetic field disappears at a few mm. below the surface. It will be seen that, under otherwise identical conditions, it is impossible to obtain the same depth effect with alternating current as with d.c. magnetization.

Magnetization by means of alternating current, however, possesses another advantage, in that complete demagnetization of the object can be carried out after testing by stepping down the current strength. With d.c. excitation, larger and more powerful auxiliary apparatus is needed in order to remove the last trace of residual magnetism.

Consideration of the physical conditions and the practical requirements has led, particularly in Germany, to the development of numerous equipments of various types.

## Technical Application†

### (a) Castings.

The flaws which can be indicated by means of the magnetic method in grey cast iron, steel, and tempered cast steel, are slag inclusions and cracks near the surface. Cracks will most frequently be found to occur in those areas in which the diameter of the section changes. They are usually due to uneven cooling during solidification. In order to achieve a sufficient depth effect, and also to ensure that flaws in all directions of the specimen will be indicated, the specimens should be clamped in various positions between the pole-pieces of powerful d.c. electromagnets and sprayed with metal suspended in oil. Thorough cleaning of the surface of the objects by sand-blasting increases the sensitivity. An apparatus specially designed for this purpose, made by Messrs. Giraudi, of Milan (see Fig. 6 on Plate 3, facing page 532), consists of a magnetic core and coil inside a housing which is closed by means of a sheet-metal trough in which the surplus oil flows back to the sump. The pole-pieces project through this sheeting and are provided with adjustable clamps. A pump is used to mix oil and metal powder and to supply the mixture. Regulating devices and a control for changing the direction of the field are also provided.

Fig. 7 (see Plate 3) shows a steel casting with small slag inclusions which would reduce the fatigue strength of the casting by about 15 %.

### (b) Worked objects and articles with treated surfaces.

Slag inclusions, cracks, or folds, may occur as a direct or indirect result of distorted holes in objects which have been worked (drawn, rolled, forged, or pressed). These flaws may be at any depth but they can only be shown up magnetically when they are near the surface. They are usually situated in definite directions which are determined by the working, and they can, therefore, be detected with a single magnetization equipment. As a rule the necessary magnetic field is obtained by passing alternating current through the longitudinal axis of the object.

A common use of the method is the testing of rolled plates for the presence of folds. These usually occur near the surface and can give rise to considerable difficulties when the plates are worked further (for instance, welding of flanges, etc.).

The principal sphere of application of the magnetic-powder method is the examination of objects of which the surface has been treated (grinding, hardening). Flaws caused by the working of the surface, such as cracks due to grinding and hardening, of course only occur at the surface, and the magnetic-powder method is particularly suited for this work. As the direction of the flaws is often at random, the field excitation is combined. By means of a d.c. electromagnet a longitudinal field is superimposed in order to detect flaws which are perpendicular to the field, whilst an annular field is obtained by alternating current for the detection of flaws in the longitudinal direction. In this manner it is possible to examine axles, spindles, crankshafts, worm gears, gears, turbine shafts, connecting rods, and machine parts. Fig. 8 (see Plate 4) illustrates a plant suitable for examinations of this kind which has been constructed for longitudinal and annular magnetization. A special apparatus for the combined magnetization of axles is shown in Fig. 9 (see Plate 4).

The acceptance testing of new parts is completed by making general tests at regular intervals. An indication of fatigue fractures in moving parts is the most usual requirement. As fatigue cracks usually occur on the surface and follow predetermined paths, it is as a rule quite sufficient to use the a.c. method in a certain direction on the part which is continually in use. An example of the magnetic testing of an object having a

* Where $e$ = bases of Napierian logarithms.
† Cf. R. Berthold: *loc. cit.*

hardened surface is given in Fig. 10 (see Plate 5); this shows numerous hardening cracks.

**(c) The testing of joints.**

A special use of the magnetic-powder method of investigation is the testing of rivet holes in order to detect any cracks between the holes. These frequently occur in boilers as a result of caustic embrittlement. For this purpose a conductor connected to a portable generator is attached to the rivet hole, and then the space between the holes is sprayed with oil. This method is extremely sensitive, and it is not necessary to grind and polish the surfaces.

The magnetic-powder method has recently become very important for the detection of surface cracks in

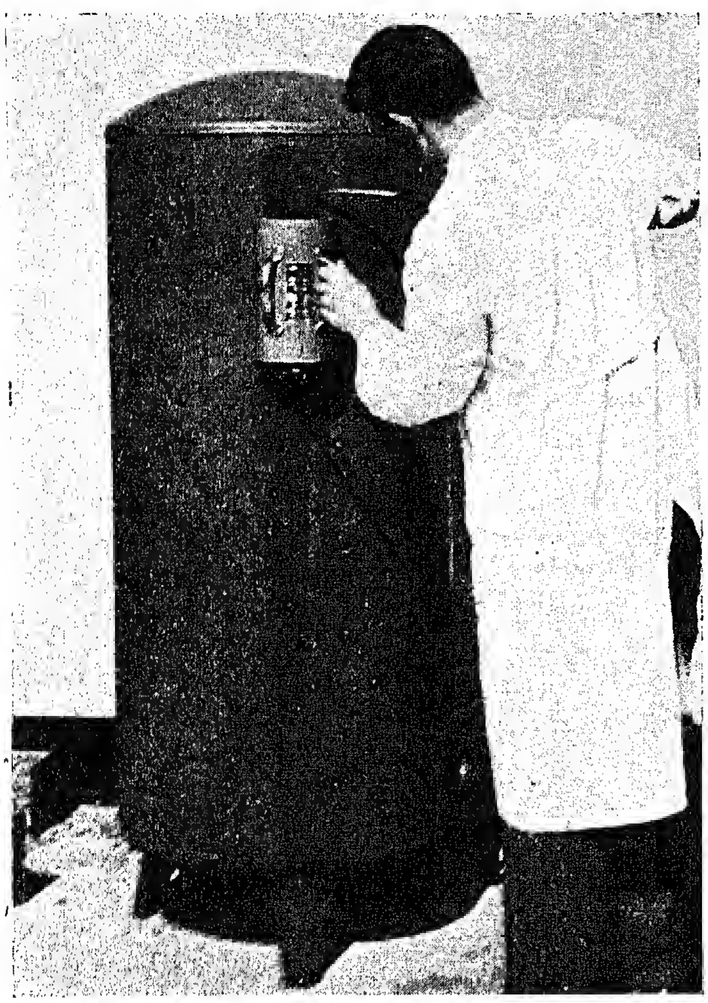


**Fig. 11.**—Tunnel magnet for the examination of thin metal welds (German State X-Ray Laboratories).

welds. A short-circuiting current is passed through the weld in the direction in which flaws are suspected.

With sheet metal up to 6 S.W.G. the magnetic-powder method can be used successfully, provided powerful d.c. fields are used for the indication of flaws in the root and also lack of fusion. Fig. 11 shows an instrument of this nature in use on a welded pressure vessel.

**(d) The testing of small objects.**

The examination of small parts can be made considerably more economical by separating the various stages of the examination, viz. magnetization, spraying, and examination. It is possible to do this with objects having a high remanence; powerful d.c. fields can be generated in the object, and after the supply has been switched off the work can be carried out with the residual magnetism Fig. 12 illustrates the circuit of this new type of apparatus. The built-in electrolytic condensers are charged by the mains and are then discharged through the object. With a plant weighing about 25 kg. an effective current peak of 4 000 amperes can be attained. This procedure is very suitable for the examination of piston rings, ball bearings, small gears, bolts, etc. Fig. 13 (see Plate 5) shows a section of part of a gear that has been tested in this manner.

**(e) Demagnetization.**

All articles which are eventually used as moving parts, or in moving parts, particularly those to be used in aircraft, must be very carefully demagnetized after testing. If the object has been magnetized by means of alternating current, demagnetization is very simple; it consists of stepping down continuously from the peak current value applied in the first instance. When the magnetization has been obtained with direct current, however, demagnetization must either be carried out in a special demagnetization apparatus, or immediately after the

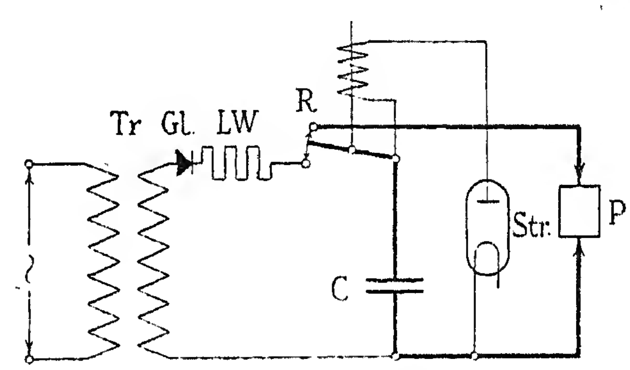



**Fig. 12.**—Circuit of the impulse apparatus (German State X-Ray Laboratories).

examination is completed the specimen must be clamped between the pole-pieces and the current must be stepped down continuously with frequent changes of the direction of the field. A demagnetization apparatus of the type referred to is illustrated in Fig. 14 (see Plate 6). If large parts are not completely demagnetized it is sufficient to place them in the magnetic North-South axis to cause remagnetization.

## (2) MAGNETIC-INDUCTIVE METHOD

### Instruments with movable coils

In view of the fact that the magnetic-powder method has no appreciable depth effect, various efforts have been made to obtain larger deflections on a measuring instrument. Among the very first instruments constructed on this principle was the I.G. welded-seam tester, based on principles laid down by W. Gerlach.*

With this method, which was primarily developed for the examination of welds (Fig. 15), two permanent bar-magnets are used to induce a weak magnetic field transverse to the welding seam. A measuring coil containing an eccentrically placed iron core, is then passed over the seam which has remanent magnetism. Sudden changes of the magnetic field over the seam, caused by changes in the permeability somewhere in the seam, excite an

* *Metallwirtschaft*, 1929, vol. 8, p. 875.

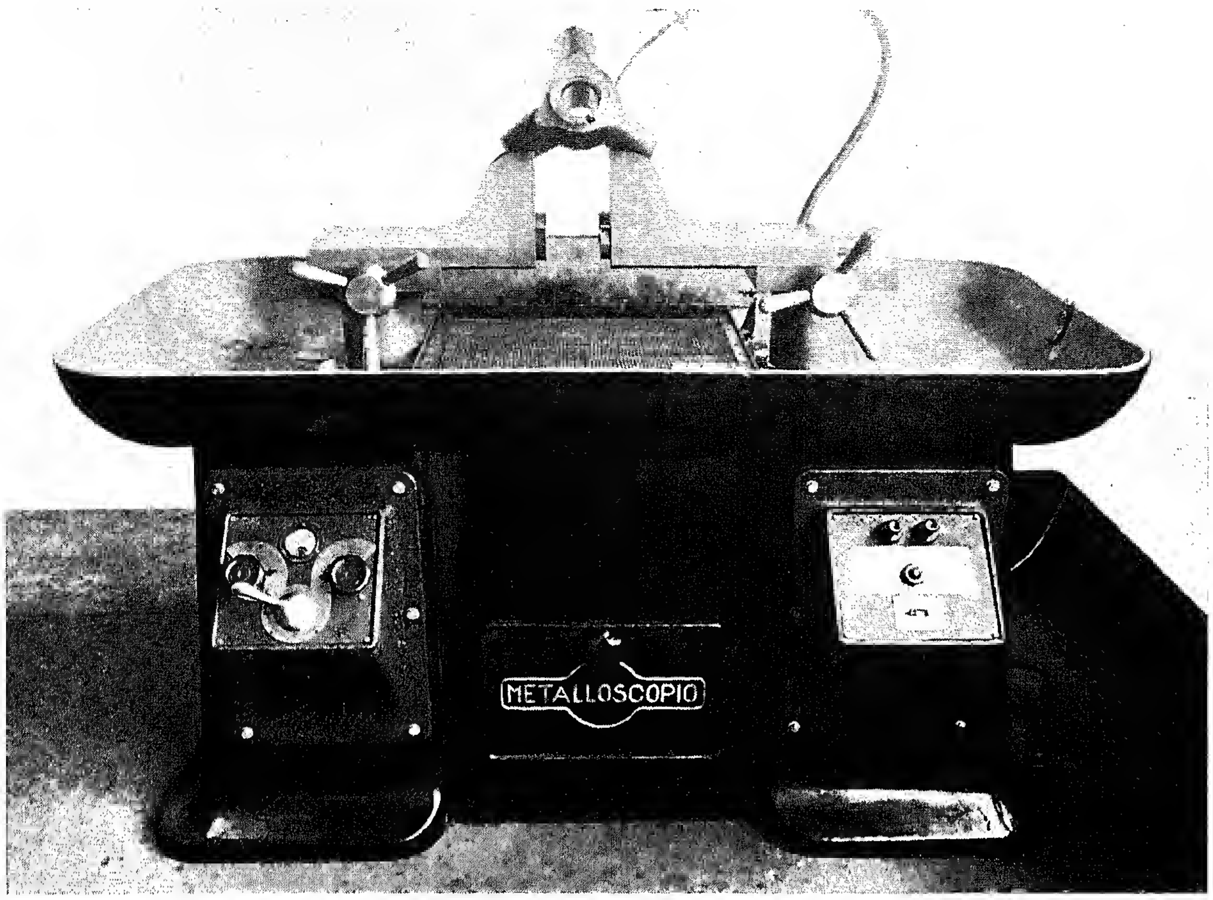



**Fig. 6.**—Metallascope (Giraudi, Milan).

**Fig. 7.**—Magnetic picture and image of the etched surface (× 200) of a steel casting with very fine slag inclusions. On right, surface showing indications made by means of magnetic powder.

(*Facing page* 532.)

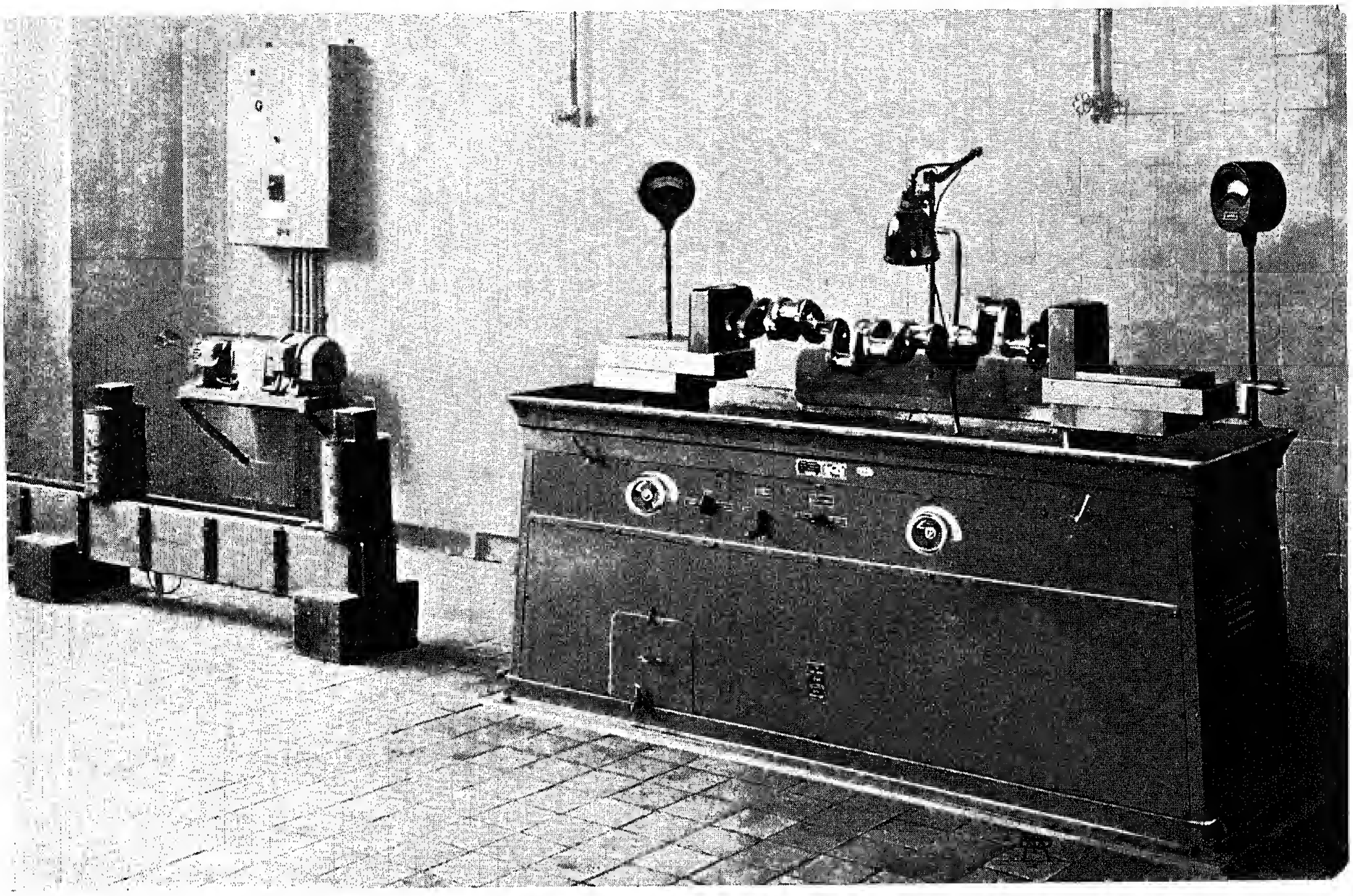


**Fig. 8.**—Combined apparatus for examinations of objects for flaws in the longitudinal and transverse directions.

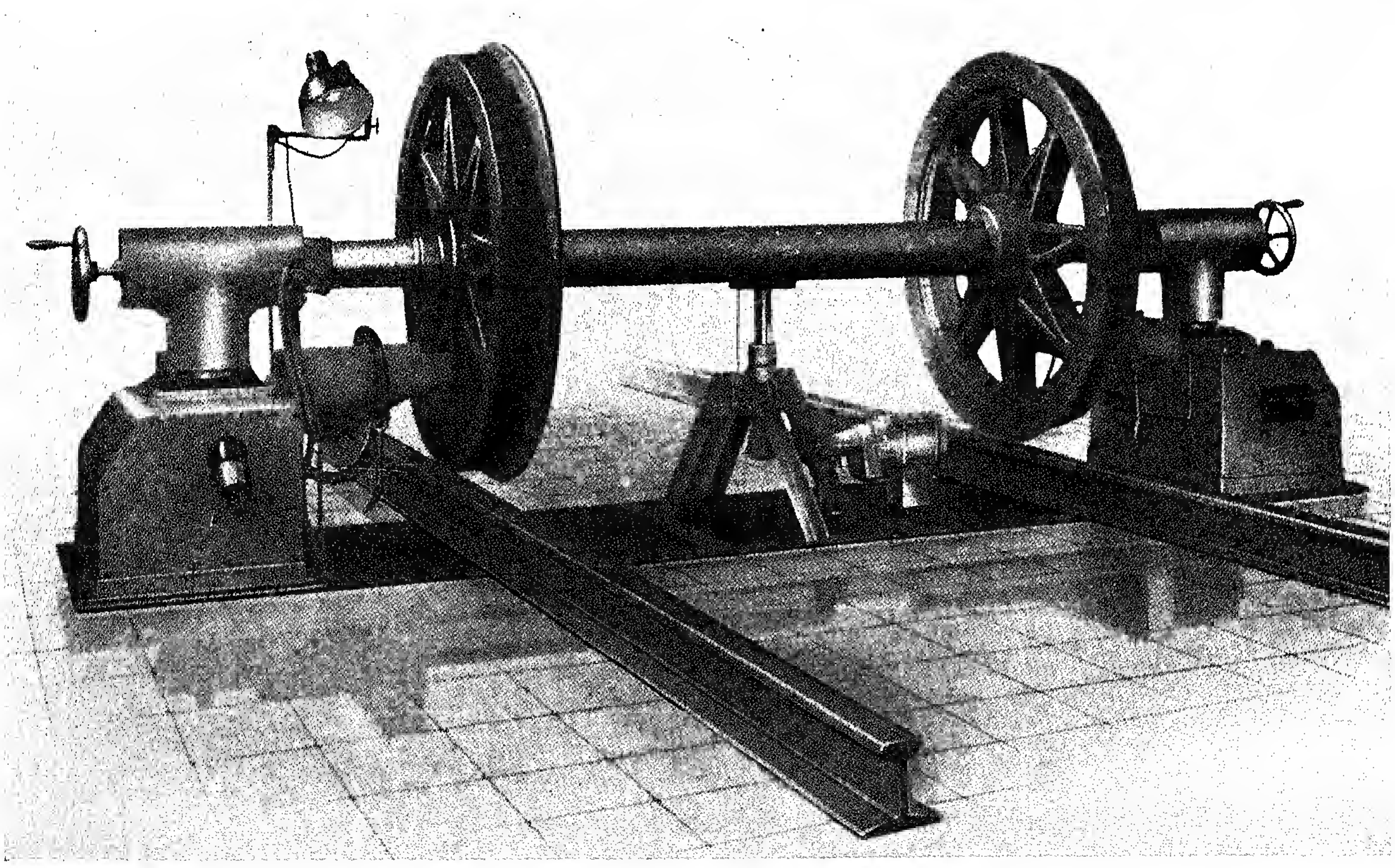


**Fig. 9.**—Testing equipment for the detection of transverse and longitudinal flaws in wheels (E. Heubach, Berlin-Tempelhof).

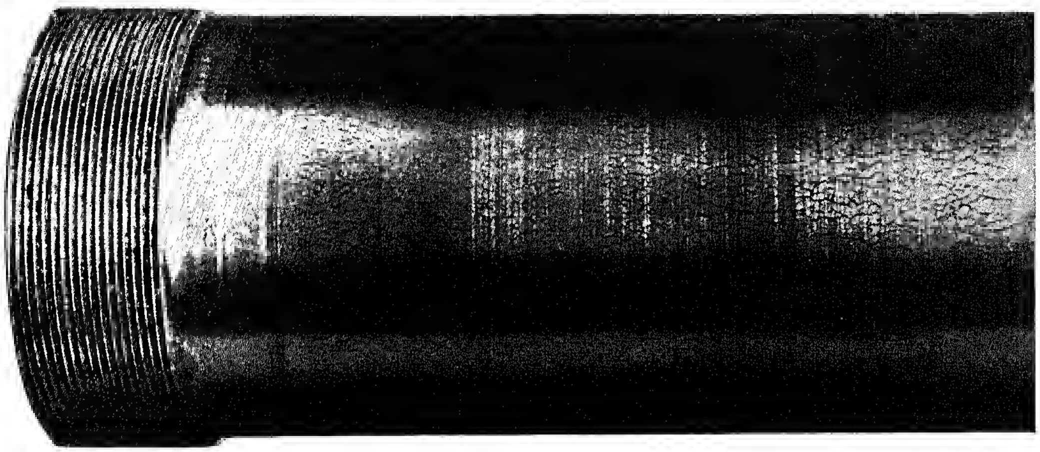


**Fig. 10.**—Bearing showing hardening cracks with 700 amp. (a.c.) flowing.

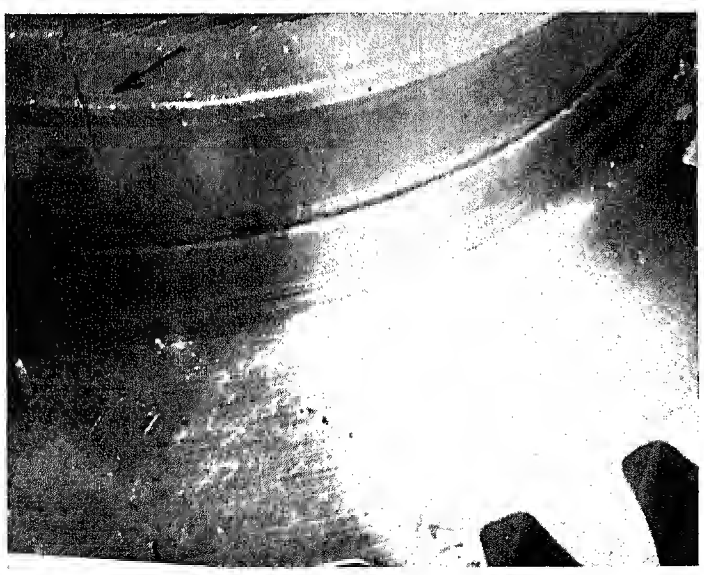


**Fig. 13.**—Section of a gear with transverse crack. Tested by the impulse method.

*Plate 6*

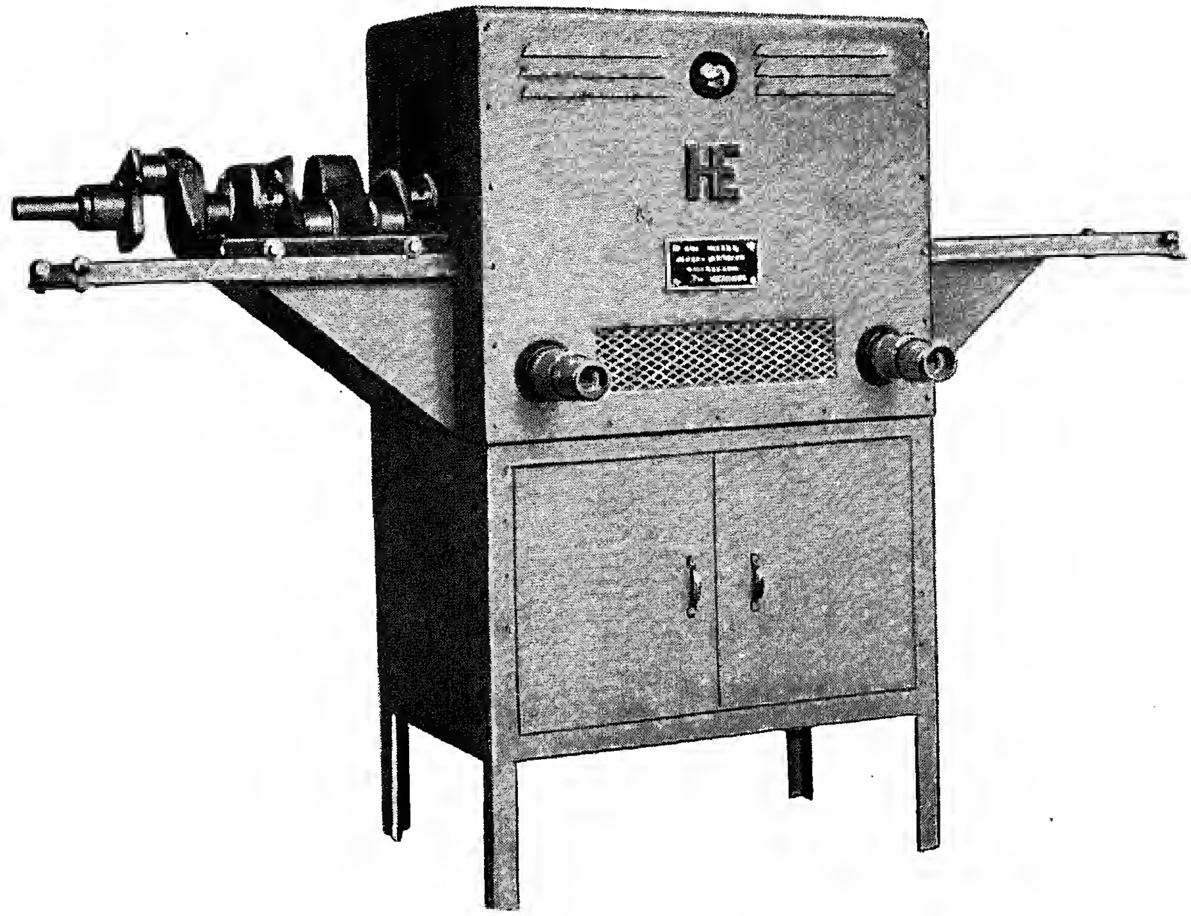


**Fig. 14.**—Demagnetization apparatus for large objects (E. Heubach, Berlin-Tempelhof).

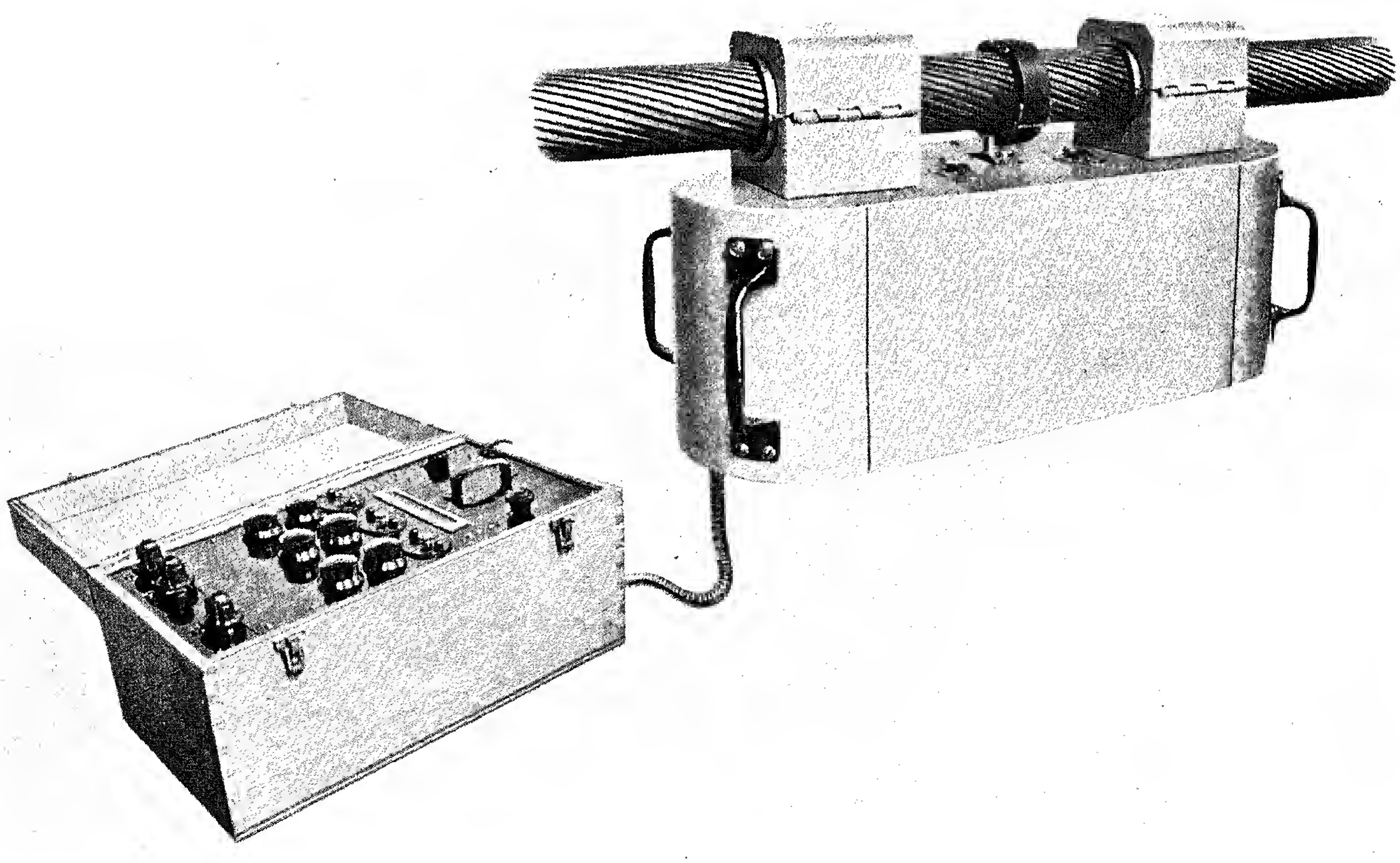


**Fig. 16.**—Examination equipment for steel cables (R. Claren, Düsseldorf).

electromotive force in the measuring coil, and this is conducted via an amplifier to the measuring instrument.

The extreme sensitivity of this instrument to every change in permeability is nevertheless a disadvantage. With investigations of magnetic objects not only the coarse structural flaws are indicated but also differences in the joint, the various zones of hardness, and similar changes in the permeability. This makes interpretation very difficult; but this can be overcome with very strong magnetic fields. Differences in structure mainly affect the initial permeability much more than the permeability obtained when magnetic saturation has been achieved. At present, however, the I.G. welded-seam testing equipment is only suitable for the examination of welds which have been annealed, but it can be used for the investigation of objects and components possessing a uniform structure.

The last-mentioned requirement is fulfilled by steel cables; the possibility of testing these has always caused considerable interest. A special apparatus developed in

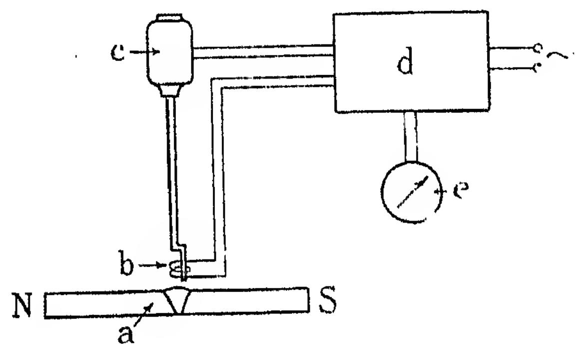



**Fig. 15.**—Circuit of the I.G. welded-seam tester.

(*a*) Welded object with remanent magnetism.
(*b*) Coil with rotating core.
(*c*) Driving motor.
(*d*) Switching device with amplifier.
(*e*) Indicator for flaws.

the German State X-Ray Laboratories for the examination of steel cables incorporates the basic principles of the I.G. welded-seam tester. In order to obtain a sufficient depth effect a very powerful magnetic field is induced in the cables (see Fig. 16 on Plate 6). The pole-pieces can be opened and the cable is placed in the circular openings provided; the pole-pieces then induce a powerful magnetization by means of a d.c. electromagnet. Between the pole-pieces, which slide over the cable, a measuring ring consisting of 3 single coils has been mounted; these can also be opened. This measuring instrument is vibrated at high speed by means of an electromotor.

Breaks in the wires of the cable generate corresponding electromotive forces in the three measuring coils; these forces are sufficiently large to be conducted to light-measuring instruments without the necessity of amplifiers. The three deflections are observed at the same time, or may be registered on a film. As the magnitude of the electromotive forces induced in each of the coils depends upon the distance between the flaw and the measuring coil, it will be seen that conclusions regarding the position of the flaws may be made from a comparison of the deflections.

The indications are not dependent upon moving the instrument or the wire.

The possibility of determining flaws and their location with three coils can only be adopted for the detection of flaws in enclosed cables. With stranded cables sinusoidal indications are obtained because of the periodic variation of the distance between the strands and the measuring instrument. For this reason the coils are connected one behind the other, and the instrument measures the sum of the electromotive forces.

According to present investigations it is possible to detect flaws up to 0·5 % of the cross-section with enclosed cables having a diameter of 50 mm.

### Equipment with stationary coils

It is possible to make use of stationary coils as well as moving coils, provided specimen and measuring instrument are moved in relation to each other, or when an a.c. field is used for magnetization. The first method is incorporated in the cable-testing device of von Wever and Otto* used at the cable-testing station at Bochum. With this apparatus (Fig. 17) two excitation coils with a total of 100 000 ampere-turns are wound round the cable; the measuring coil, consisting of two single coils differentially connected, is situated between the excitation

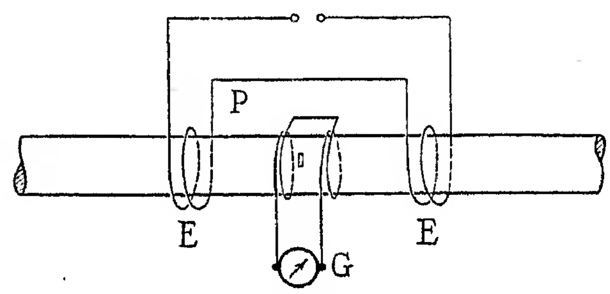



**Fig. 17.**—Circuit of cable tester (Wever and Otto).

E = excitation coils.
P = testing coil, differentially connected.
G = ballistic galvanometer.

coils. Flaws in the section of the cable, which should be moved at a uniform rate between the two coils, generate a current impulse which is supplied to a ballistic galvanometer. Special winding devices have been originated for winding and unwinding the coils. According to the authors the flaws indicated are 0·3 % of the cross-section.

The possibility of applying alternating fields in combination with stationary coils has been developed in different ways for special cases. The principal object will be to determine changes in the joint, or to measure the degree of hardness (magnetic hardness-tester made by Messrs. S. K. F. Norma A.G.).† This apparatus measures the phase displacement which occurs when a laminated ring is brought near to the field of an excitation coil. The displacement is measured by means of secondary coils and a galvanometer.

An attempt to make the combination of stationary coil and alternating field more generally useful is represented by the equipment recently developed by the German State X-Ray Laboratories. It has been designed for the examination of bars and tubes for cracks and slag inclusions (Fig. 18). The equipment consists of two excitation coils connected one behind the other, and two measuring coils connected in opposition. The excitation

* *Zeitschrift des Vereins deutscher Ingenieure*, 1932, vol. 76, p. 557.
† *Kugellager-Zeitschrift*, 1929, p. 43.

coils induce eddy currents in the walls of the specimens; the extent of these currents depends upon the conductivity of the walls of the specimen. If this conductivity is impaired by means of a longitudinal crack, then the eddy-current field and, as a result, the opposing inductance, will be smaller than in the sound section. Thus, different currents will be induced in the measuring coils and can be measured by means of an amplifying arrangement.

The application of this method to steel tubes and bars

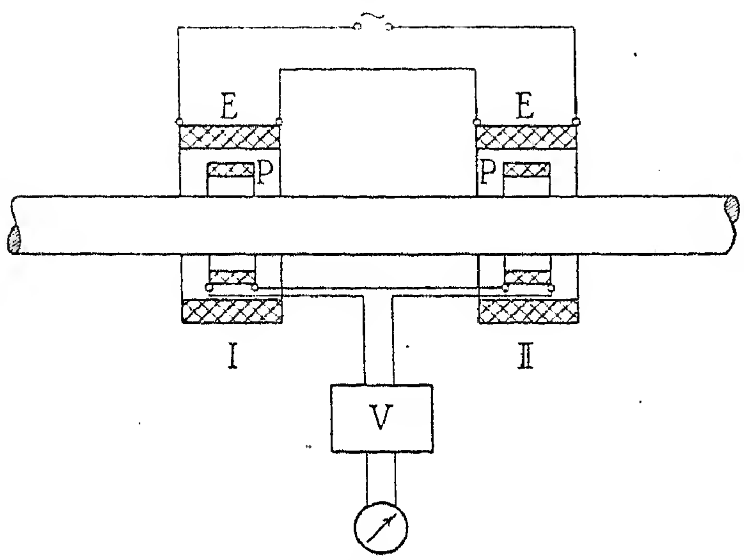



**Fig. 18.**—Principal circuit of a tube- and bar-testing instrument (German State X-Ray Laboratories; made by R. Claren, Düsseldorf).

E = excitation coils.
P = testing coils.
V = amplifier.

occasionally causes difficulties of interpretation, difficulties caused by the well-known influences of hardness zones and uneven joints. These difficulties, however, completely disappear in the case of materials which cannot be magnetized (light metals, copper, and brass). The sensitivity and accuracy in the indication of longitudinal cracks is in these cases very high.

### (3) MEASUREMENTS OF DIELECTRIC LOSSES

A non-destructive method of testing based on purely electrical principles is the measurement of dielectric losses. This method has been developed to determine the condition of the insulation of high-voltage apparatus, in particular of transformers, condensers, cables, etc. The condition of the insulation is indicated in its relation to the voltage supplied or the temperature of the dielectric.

With this method of testing, the loss angle is determined by means of the Schering bridge,* the tangent of the angle being indicated by the ratio of the effective current to the wattless current of the high-voltage apparatus (tan $\delta$ measurement).

Faults in the condition of the insulation usually lead to a measurable increase in the dielectric losses, long before there is any danger of breakdown. Hence it is possible to check the entire high-voltage plant with regard to its electrical safety without interference and without endangering its efficiency by applying considerably higher test voltages. These methods of electrical testing are comparable with the mechanical safety tests carried out on large structures; in those cases, too, it has often been the case that overloading, although temporary, has had a detrimental effect, as it leads to fatigue strains which eventually endanger the structure. The tan $\delta$ values originally obtained in relation to temperature or voltage can, as Keinath† has shown, be rapidly and continuously registered and recorded with the aid of a special recording device. By this means continuous control can be applied to an entire electrical system or to single parts. In addition to being used to control apparatus, the tan $\delta$ measurement can also be used to determine the most suitable shape and application of insulation (insulators, paper condensers, cables, etc.). The dielectric method of measuring losses has also been found to be excellent for the examination of articles and objects. Fluid dielectrics (mineral oils) have been investigated in this manner in order to determine the extent of the influence of dampness, oxidation, etc. These cannot be obtained directly from measurements of acid content, deterioration factors, and dielectric strength.

Similar considerations apply to the examination of ceramic substances to gauge their reaction to various voltages and temperatures. Finally the examinations were extended to the measurements of filling agents of plastic insulation material, in order to determine the degree to which dielectric losses depend upon the temperature.

* H. Schering and A. Burmeister: *Zeitschrift für Instrumentenkunde*, 1924, vol. 44, p. 98.
† G. Keinath: *Archiv für Technische Messung*, 1933, vol. 6, p. 339.

[The discussion on this paper will be found on page 580.]

# RADIOGRAPHY—AN ASPECT OF NON-DESTRUCTIVE TESTING

By V. E. PULLIN, C.B.E.*

(*Paper received 23rd September, and read at a meeting arranged by the* JOINT COMMITTEE ON MATERIALS AND THEIR TESTING, *25th November*, 1938.)

## INTRODUCTION

The examination of structures, directed to the discovery of flaws and defects, by X-rays and radium must be regarded as a part of the whole subject of non-destructive testing. It has been the experience of the author that radiological testing is incomplete in very many cases without the use of such complementary methods of testing as may become apparent in the course of any particular investigation.

Radiological testing may be subdivided into three main groups:—

(1) The examination of structures by X-rays to discover gross flaws such as porosity, cracks, blow-holes, and inclusions, and also, in the case of built-up articles, to check internal assembly.

(2) The examination by gamma rays directed to the same objects as (1).

(3) The examination of structures by X-ray crystal analysis methods in order to investigate certain properties and ascertain particulars concerning the crystalline condition in so far as this may have a bearing on the problem concerned. (This aspect of the science of X-ray crystal analysis is referred to distinctively from the larger or research sphere of this work, which is, of course, a laboratory conception.)

The examination of metallic structures by X-rays was first started by the author at Woolwich some 22 years ago, when the method was applied to the detection of flaws in certain warlike stores and was found, after some preliminary experimental work, to be of considerable value. Since that time the subject of engineering radiography has made very rapid strides in all directions until, at the present time, it has many highly important uses in the sphere of engineering and industry generally.

The rapid progress of metal radiography has been materially advanced by the progressive excellence of apparatus. As a result of research in this and other countries, modern apparatus has reached such a stage of perfection that many of the early technical difficulties met with in this work have disappeared. The X-ray apparatus installed by the author in the Research Department at Woolwich in 1917, for the examination of certain military stores, was equipped with an old-fashioned induction coil of uncertain performance, and the tube was one of the early models of the hot-cathode type due to W. D. Coolidge. Figs. 1 and 2 illustrate one of the X-ray equipments now installed in the same laboratory. It is a modern design of high-voltage transformer for 600 000 volts manufactured by Messrs. Philips, of Holland, the X-ray tube being a 300 000-volt tube made by the same firm. In place of the circumscribed operating space in the original installation, a large room is now allocated to the disposition of specimens, the tube and its accessories being part of an overhead trolley system and capable of being moved to various parts of the room as required. The movements of the tube are controlled by electric motors.

One of the early difficulties inherent in this work was the provision of safety devices to ensure protection for the operator. This was a serious problem and demanded much thought in order that the necessary flexibility of operation might be preserved. At the same time its necessity very much increased the difficulties of the general technique. In modern apparatus we have now attained a very high standard with regard to safety in design; and the dangers of X-ray manipulation no longer assume the alarming proportions they did in the early days of radiography. Modern apparatus constructed by reputable makers is electrically shockproof; even the high-voltage cables may be earthed and consequently used perfectly safely in a crowded environment. X-ray tubes are no longer the fragile and dangerous pieces of apparatus they were, but are now constructed on a very robust scale and are free from danger due to escaping X-rays and electrical shock. These two factors have revolutionized the application of X-rays to engineering purposes, because it is very often necessary to apply this method of inspection in busy shops and factories and to operate it by personnel unfamiliar with the potential danger of the method.

The penetration of metals by X-rays is governed very largely by the voltage applied to the X-ray tube. In the early days this voltage was limited by the tube itself—it was not possible to apply more than 100–150 kV without serious risk of breaking the tube. This meant that effective X-ray penetration was limited to something of the order of $1\frac{1}{2}$ in. of steel. Nowadays, it is possible to obtain tubes that will run successfully at a potential of 1 000 000 volts and upwards across their terminals, and it is everyday practice to employ X-ray tubes for this work operating at voltages of 250–350 kV. Thus, it is now a matter of common practice to examine steel structures 4 in. and even more in thickness by X-rays.

During the last 20 years, important strides have been made in one of the most vital branches of this work, which is interpretation of X-ray pictures and the definition of the significance of the various radiographic shadows in engineering terms. It is perhaps in this branch of the work that the greatest progress has been made, and it is to this sphere that the author's research has, to a great extent, been directed. By X-raying large

* Formerly with Research Department, Woolwich.

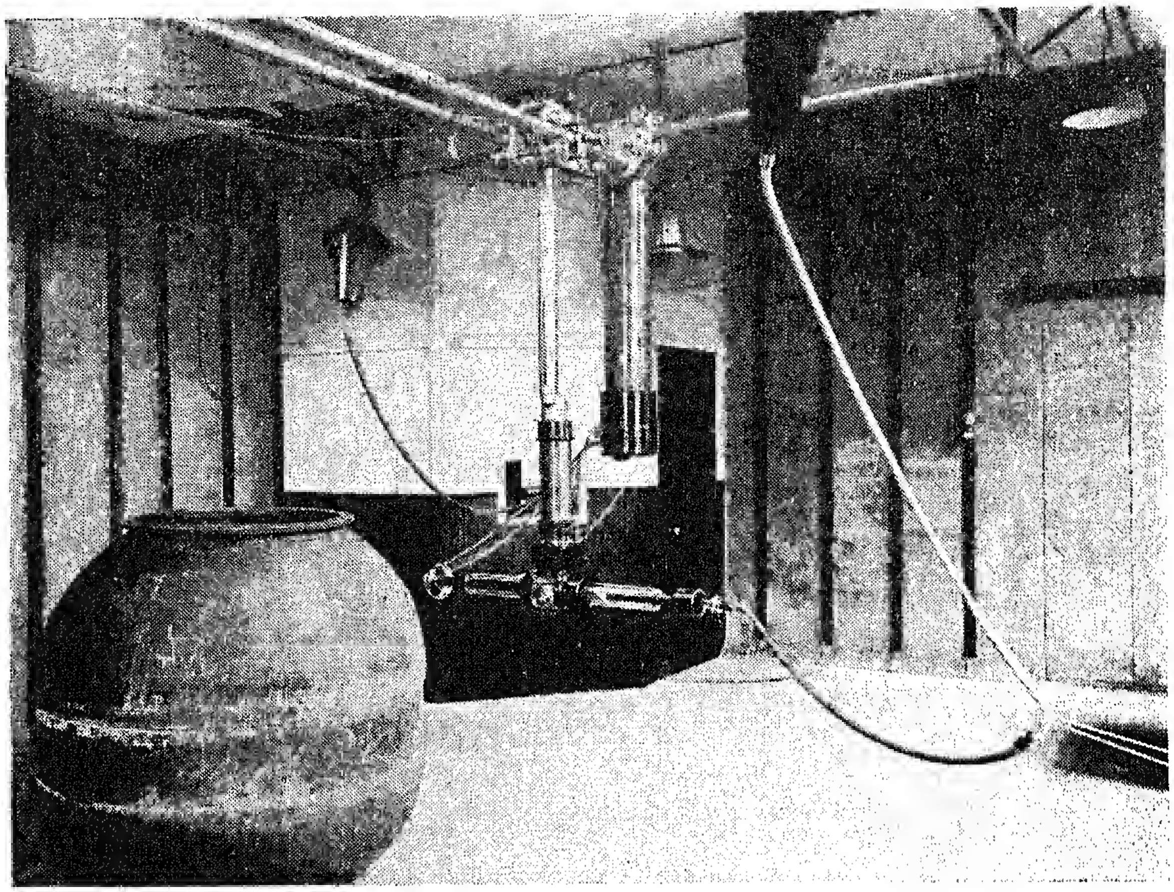


**Fig. 1.**—X-ray tube on overhead trolley system at Radiological Laboratory, Woolwich.

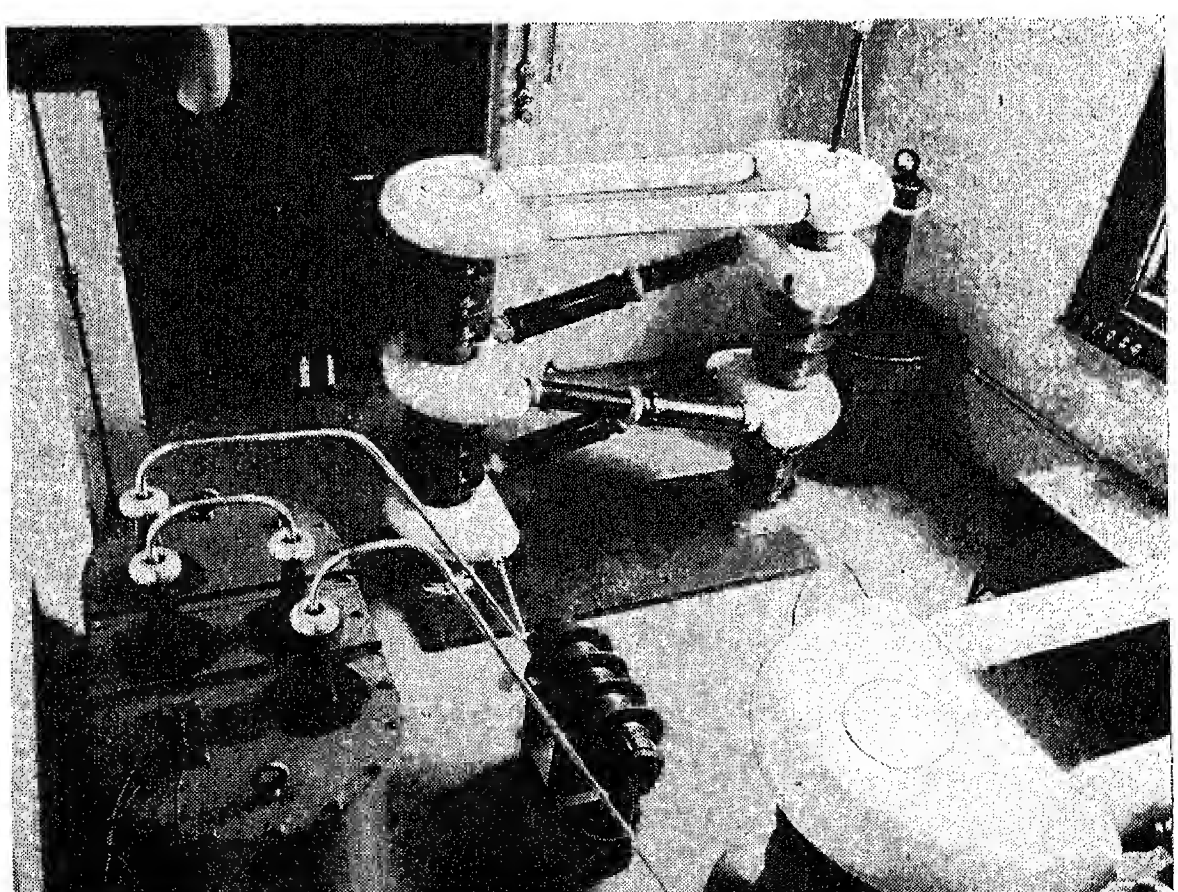


**Fig. 2.**—600-kV X-ray equipment at Radiological Laboratory, Woolwich.

quantities of castings and forgings and metallic structures generally, and subsequently dissecting them and comparing the sections with the radiographs, it has been possible to prepare a sort of radiographic atlas by which interpretation of radiographs is more or less standardized.* At the same time, the interpretation of engineering radiographs is, of necessity, very largely a matter of experience. It depends essentially upon the use of a correct technique in making the exposure.

The next main branch of progress in this work has been concerned with technique, and in this connection the radiological research laboratory has collaborated with the makers of photographic films and intensifying screens. With the improvement in apparatus, particularly as regards the use of high voltages and better focusing devices, exposures have been very considerably reduced, especially in the last few years. To this very desirable economic end the makers of films and screens have contributed enormously. There is still room for improvement in this direction, and research is proceeding along lines which show great promise of success and indicate an even wider and more economic use of this method of inspection.

One of the most serious defects encountered in the development of this subject has been associated with the phenomenon known as scattered radiation. When X-rays are passed through any material the beam of rays suffers certain modifications; part of it is scattered much as visible light is scattered by fog, part of it is transformed into radiation of a different character, part of it may be said to be absorbed in the material. Scattered radiation has an actinic character, and therefore, if allowed to reach the photographic film, will produce fogging and reduce the contrast, and so will militate against the perception of detail. It must be remembered that the only useful component of the X-ray beam in radiography is the one which passes through the flawed area to the photographic film, and so produces a definite shadow on it. At the same time, scattered radiation from many angles also reaches the film not only from the specimen itself but from surrounding objects, from the screens, from the cassettes, and from the atmosphere. It is necessary, therefore, in the production of a good radiograph to eliminate, as far as is possible, this unwanted scatter.

For example, it has been found that when X-raying steel of thicknesses of 2 in. and upwards, it is necessary, if all relevant detail is to be shown, to eliminate scattered radiation by the introduction and use of a piece of apparatus known as a Potter–Bucky grid, which is, in effect, an arrangement of lead slats placed in such a position as to absorb angular radiation from the specimen and prevent its reaching the photographic film. This apparatus, however, is found to be unnecessary when radiographing steel under 2 in. in thickness.

The question of the effect of scatter on the resulting radiograph is closely bound up with photographic films and intensifying screens. Research is now in progress in the Research Department to investigate the combined effects of these factors on the detail to be obtained in engineering and industrial radiographs. In the first place it is necessary to show the difference between (1) radiographs obtained by direct X-ray beam, when all except an incidentally forward scatter is eliminated; and (2) radiographs obtained by the total amount of radiation, i.e. the direct beam plus all scatter. The method adopted in these experiments is to pass the beam of radiation through two holes of comparatively small diameter ($\frac{3}{8}$ in.) drilled in two metal plates separated by a distance of 22 in. This has the effect of stopping any rays at an angle of more than 1° (approximately) from the normal ray. The image on the film, therefore, is only $\frac{3}{8}$ in. in diameter. On the other hand, for exposures made "with scatter" a similar arrangement is

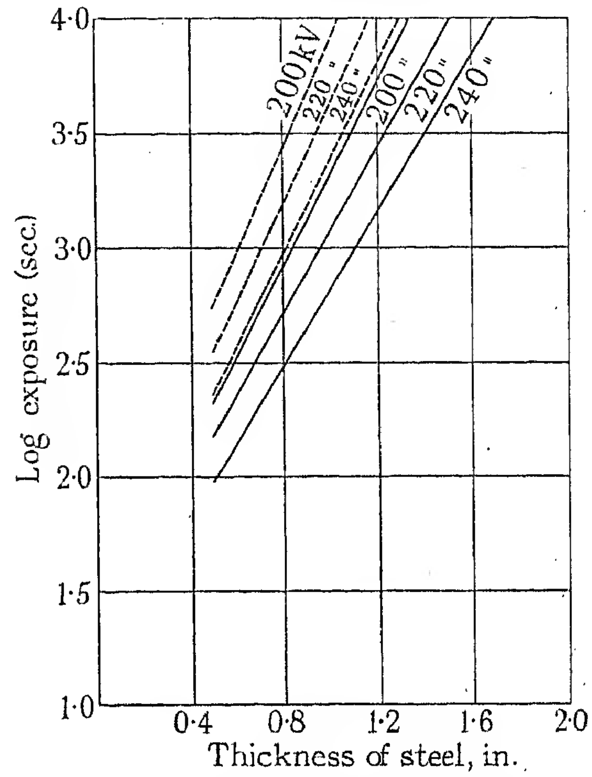



**Fig. 3.**—Results obtained without screens.
Tube current 4 mA. Anode-to-film distance 36 in.
----- Direct radiation.
——— Total radiation.

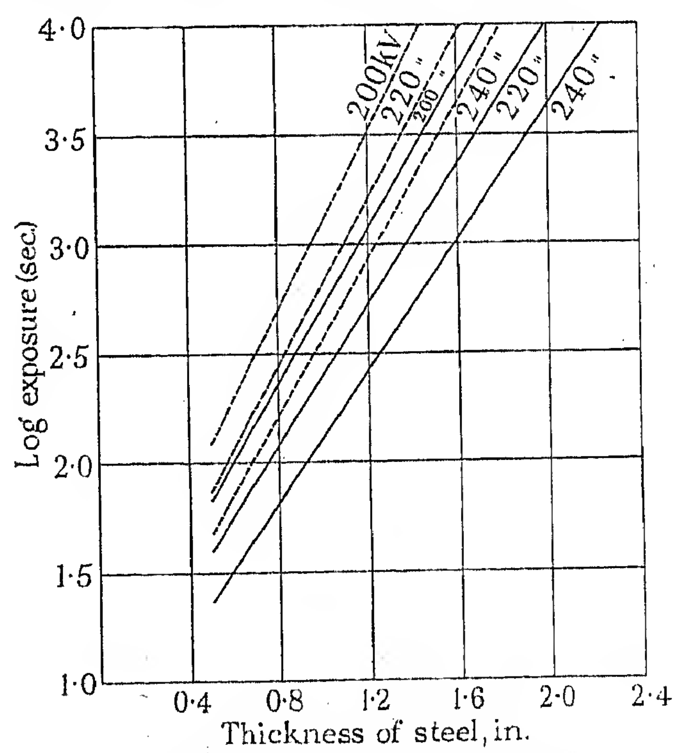



**Fig. 4.**—Results obtained with lead screens.
Tube current 4 mA. Anode-to-film distance 36 in.
----- Direct radiation.
——— Total radiation.

* V. E. Pullin: "Engineering Radiography" (G. Bell and Co., London).

used but with the apertures enlarged so as to irradiate a circle of about 6 in. diameter on the metal surface. In this case the metal is placed near to the film and the back diaphragm aperture is enlarged to allow scatter from the whole of the irradiated metal to reach the film. Figs. 3, 4, and 5 show exposure curves obtained under different conditions. The dotted lines represent the direct radiation exposures and the full lines the total radiation exposures. It will be observed that the logarithm of the exposure time is plotted against thickness of steel in inches. Reference to these curves, e.g. Fig. 5 (240-volt curves), shows that at a thickness of 1·6 in. of steel the "with scatter" exposure includes nearly 10 times the amount of scatter of the direct radiation exposure.

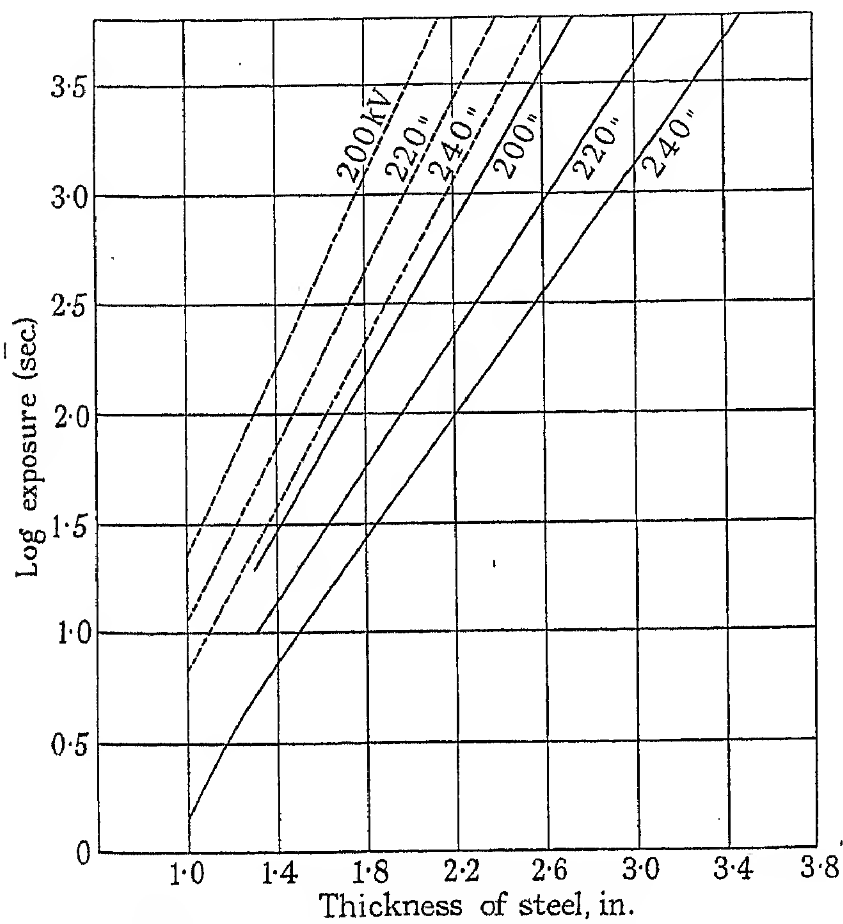



**Fig. 5.**—Results obtained with salt screens.

Tube current 4 mA. Anode-to-film distance 36 in.
- - - - - Direct radiation.
——— Total radiation.

Fig. 6 has been deduced from these exposure curves and shows the proportion of scatter obtained in radiographs of different thicknesses of steel under different conditions, e.g. without intensifying screens, with salt screens, and with lead intensifying screens.

The use of salt intensifying screens in this particular work is more or less universal because of the enormous reduction in exposure times which they effect. This average reduction is of the order of 400 or 500 times. Such screens have, however, two very definite disadvantages. In the first place they are usually coarse-grained, and this "graininess" militates against the appreciation of fine detail in a radiograph. Secondly, it has been shown that the effects of scattered radiation are magnified by these screens in the resulting radiographs. Special films have recently been developed which are unsuitable for use with salt screens. They have, however, the great advantage of producing a much finer-grain picture with increased contrast, and are therefore particularly valuable in metal radiography. The author has found that lead intensifying screens may be used with very definite advantage in conjunction with these films with an exposure reduction factor of the order of 4. The lead screens used are 3 mils thick (front screens) and 6 mils thick (back screens).

Reference to Fig. 6 will show that when salt intensifying screens are used to examine steel 2 in. thick, the ratio of scatter to primary radiation is of the order of 10, and it is at this point that difficulty is experienced in detecting fine detail in a radiograph. It seems, then, that we must regard this factor of 10 parts of scatter to 1 of primary radiation as being the limit allowable for properly readable negatives. Therefore, if we consider the radiography of 2 in. of steel, a reference to Fig. 6 shows that using 200 kV we are just within our limiting figure of 10, but for $2\frac{1}{2}$ in. we must adopt some method of

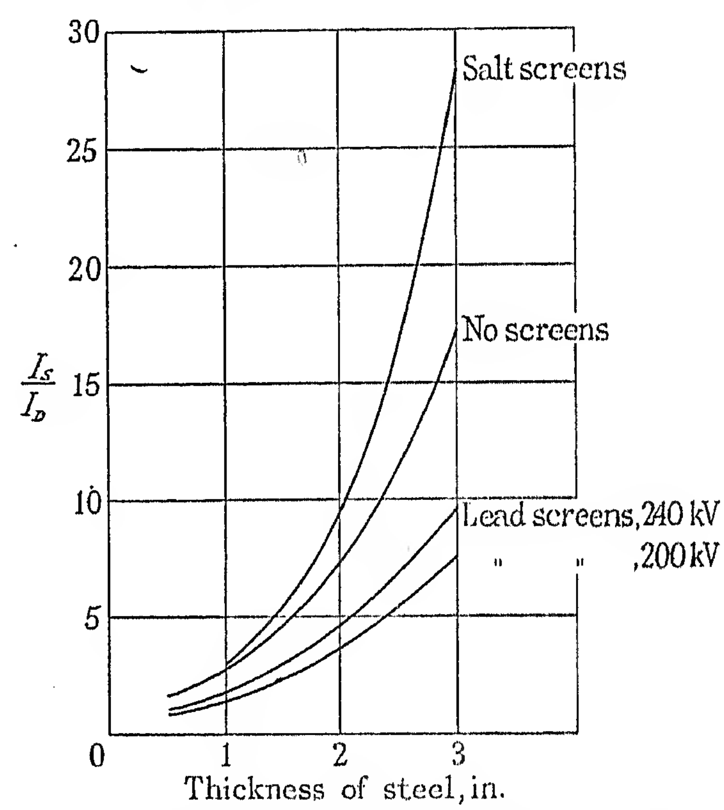



**Fig. 6.**—Ratio of intensity of scattered to direct radiation (200 kV).

eliminating scatter. We have two alternatives: either to use salt intensifying screens with a Potter–Bucky grid, which will put up the exposure some 6 times, or to use a special film with lead intensifying screens either with 200 kV or with 240 kV. Both these alternatives are well within an economic exposure time, but lead screens will of course involve a very much longer exposure than salt screens. They will, however, have the advantage of allowing much finer detail to be appreciated. Figs. 7 and 8 (see Plate 7, facing page 540) are comparative radiographs of a steel specimen (a weld), Fig. 7 relating to a 2-in. and Fig. 8 to a $2\frac{1}{2}$-in. plate. Figs. 9 and 10 are exposure curves for the special high-contrast films referred to above; Fig. 10 shows the results obtained without screens and Fig. 9 with lead screens. It will be observed that the use of lead screens reduced the exposure by about 4 times. It is, of course, important to remember that

the radiographic problem under consideration will determine the extent of refinement demanded with regard to technique. The more numerous the refinements that are introduced, the greater the cost. In the examination of high-grade welds, for example, the utmost care in radiography must be observed because the essential flaws involved are likely to be in the nature of fine cracks or discontinuities, the detection of which forms the essential *raison d'être* of the examination. On the other hand, if the problem merely involves the detection of gross flaws such as blowholes or large tears a much less refined, and therefore less expensive, examination will suffice.

It is customary in metal radiography to employ cassettes backed with lead for enclosing the photographic film and intensifying screens. Experience has shown that back scatter from the lead has a very considerable fogging effect on the radiograph, especially at voltages of about 200 kV and over, and it is the author's practice to interpose between the lead backing and the salt screen a sheet of brass some 30 mils in thickness, and another sheet of thin cardboard in front of the brass to protect the film from back scatter and beta rays. This contingency of course does not arise when lead intensifying screens are used (the back one being 6 mils in thickness). Figs. 11 and 12 (see Plate 8) show radiographs of a light alloy metal tube containing a heavy filling. Fig. 11 was obtained on ordinary film without screens, and Fig. 12 on special film with lead intensifying screens. The difference in the detail of the disposition and state of the filling is obvious.

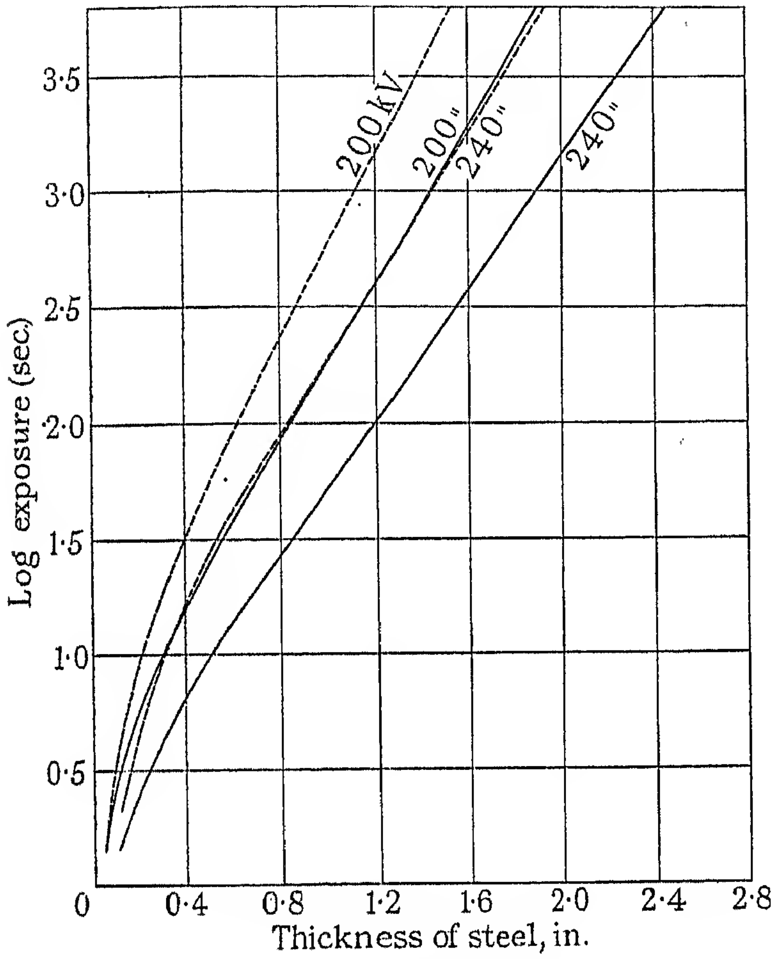



**Fig. 9.**—Results obtained with lead screens, using special film.

Tube current 4 mA. Anode-to-film distance 36 in.
----- Direct radiation.
——— Total radiation.

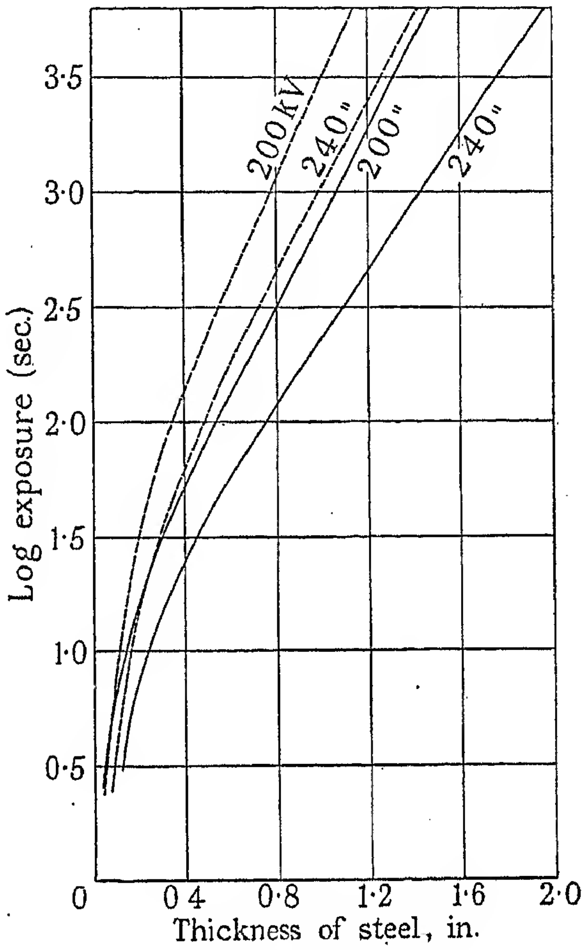



**Fig. 10.**—Results obtained without screens, using special film.

Tube current 4 mA. Anode-to-film distance 36 in.
----- Direct radiation.
——— Total radiation.

## PLANAR RADIOGRAPHY

A further refinement in technique has many specialized applications in engineering work, especially to the examination of built-up structures. The principle is well known in medical work and has been described under various titles such as "tomography," "laminography," "planegraphy," and so on, but the term "planar radiography" appears to the author to be the most appropriate one. If, during the exposing of a radiograph, the X-ray tube and the film are kept in steady motion along parallel lines but in opposite directions, the shadow recorded on the film of any object placed between them will in general be blurred and indistinct, but there is always one plane situated somewhere between them to which this does not apply. The shadow of anything lying exactly in this plane will be as sharply defined as it would have been had no movement taken place. Anything lying in a plane on either side of this plane of definition will become blurred in the radiograph, the diffusion increasing as the distance from the definition plane increases. By making use of this principle it is possible to obtain well-defined radiographs of a particular plane in a specimen, with the shadows of other planes, which might obstruct the detail required, blurred and, as it were, smoothed out.

Fig. 13 illustrates the principle. In this, equal move-

ment of tube and film is shown, and the sharply defined plane lies exactly midway between. It will be seen from the diagram that a ray passing through any spot in this plane always arrives at the same spot on the film, whatever positions the tube and film have reached along their respective paths. Fig. 14 shows the effect of making the range of movement of the film smaller than that of the tube. The plane of definition has approached nearer to the film and it can be shown that any spot on this plane will remain sharply defined. The position of the definition plane is thus controlled by adjusting the ratio of tube and film movements.

In industrial radiography it is frequently more convenient to move the specimen rather than the tube, and so a modification of the method has been employed in which the tube is kept stationary while the film and the specimen are put into relative motion, thus effecting a considerable simplification in the apparatus required.

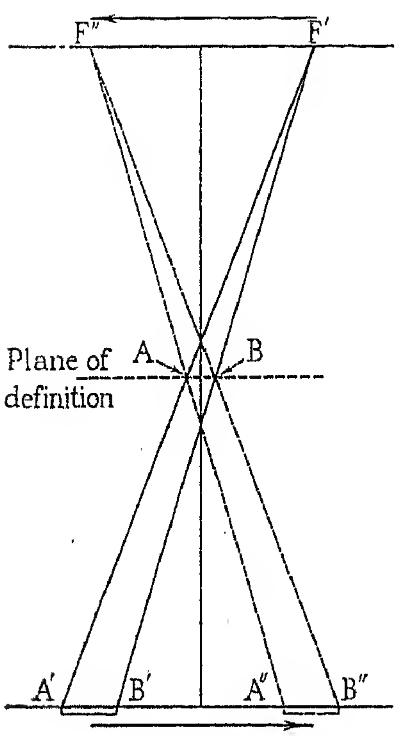



**Fig. 13**

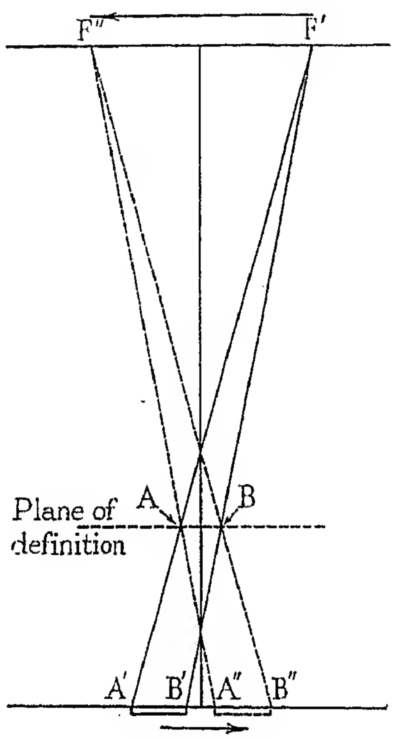



**Fig. 14**

The specimen and the film move together in the same direction but at different rates, the film travelling slightly faster than the specimen. The greater the difference in their rate of travel the farther the plane of definition recedes from the film. As before, by adjusting the relative rates of travel it is possible to obtain a defined radiograph of any plane required.

Fig. 15 (see Plate 9) shows the results of applying this method to an experimental test specimen. The specimen was a pile of steel plates of a total thickness of 1 in., arranged as shown in the diagram. The three $\frac{1}{16}$-in. plates had small holes drilled in them forming a different pattern on each plate—a triangle, a square, and a circle, in the order shown. The first radiograph is taken in the normal manner and shows all the holes but gives no indications of their position in the specimen. The other three are planar radiographs with the plane of definition arranged to coincide with each of the three drilled plates in turn. It will be seen that the lowest of the three plates (with the circle pattern) is separated from the next plate by $\frac{1}{4}$ in. This separation is sufficient to show the circle of holes very clearly, with the others very much blurred. Between the other two plates there is only $\frac{3}{16}$-in. separation, and consequently the distinction between the two patterns is not so marked.

## VISUAL X-RAY EXAMINATION

With the widespread adoption of light alloy castings, particularly in aircraft construction, the use of visual X-ray examination has increased considerably in the past few years. Specially designed equipment is essential for this work because experience has shown that visual examination can only be efficiently carried out if the specimen is kept in constant movement. This movement can only properly be achieved manually, and therefore the question of safety for the operator becomes an all-important question in the design of apparatus. Further, the operator should never be allowed to gaze directly at the fluorescent screen, however well it may be protected by lead glass. His observations should always be made indirectly by means of a mirror.

Visual X-ray examination is perfectly effective and reliable for the generality of aluminium alloy castings, but it has not been found to be reliable in the case of magnesium alloys because one particular type of defect to which such specimens are liable, known as inter-crystalline porosity, is much too fine in character to be appreciable on a fluorescent screen. Such specimens should in any case be examined radiographically.

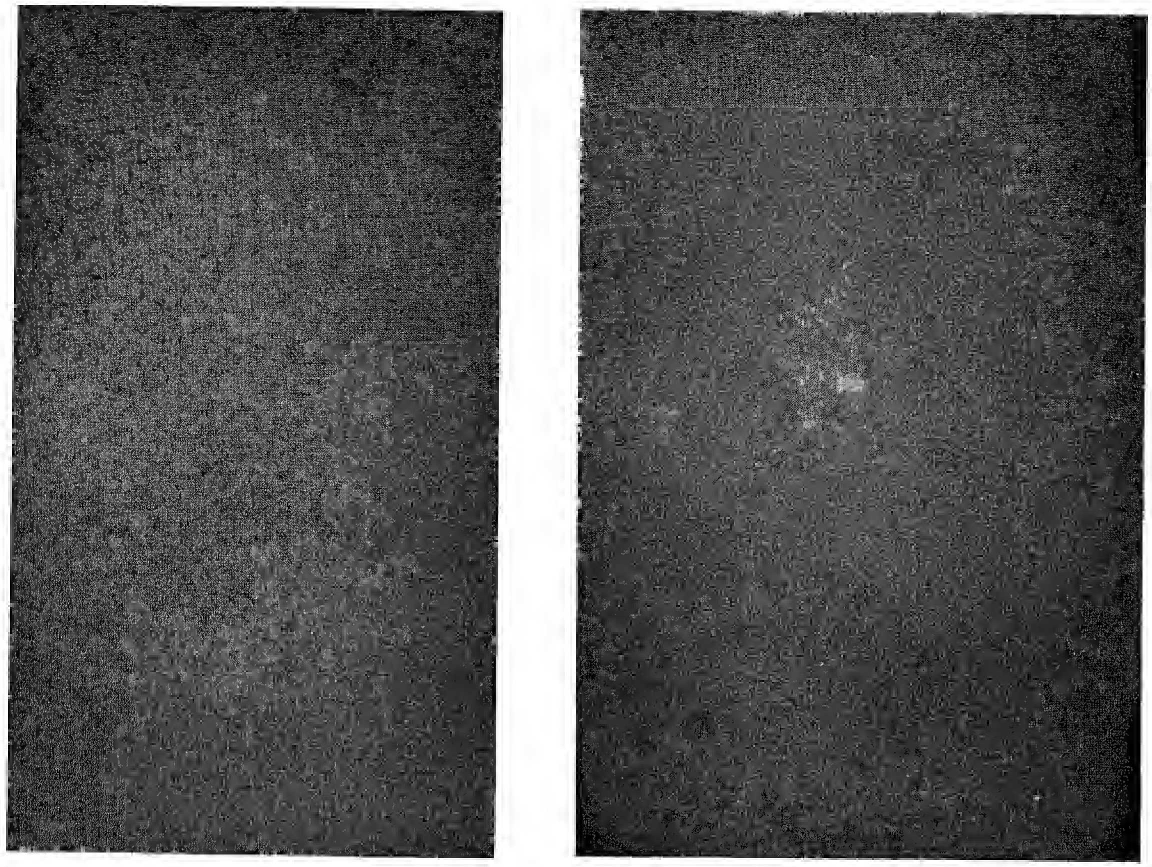
X-ray examination is of outstanding value in the examination of welds and it may be said that it will inevitably be recognized in this country, as it is in America, as the standard acceptance test for all important welded joints. Weld radiography is a specialized branch of the subject and demands careful and well-defined technique; moreover, it postulates a considerable knowledge, on the part of the radiologist, of the science of welding. This science has advanced so much in the last two or three years that the defects inherent in it have become much reduced and have changed considerably in character. It has therefore been found necessary to modify radiological technique so that it may fulfil its function as an ultimate criterion of weld excellence. Every refinement known to radiological practice must be used with meticulous care if the small but vital defects incidental to modern welding are to be infallibly detected.

The success of engineering and industrial radiography generally depends, first, to a very large extent upon the selection and layout of truly appropriate apparatus for the particular work to be done, and secondly upon sound technique.

## RADIUM

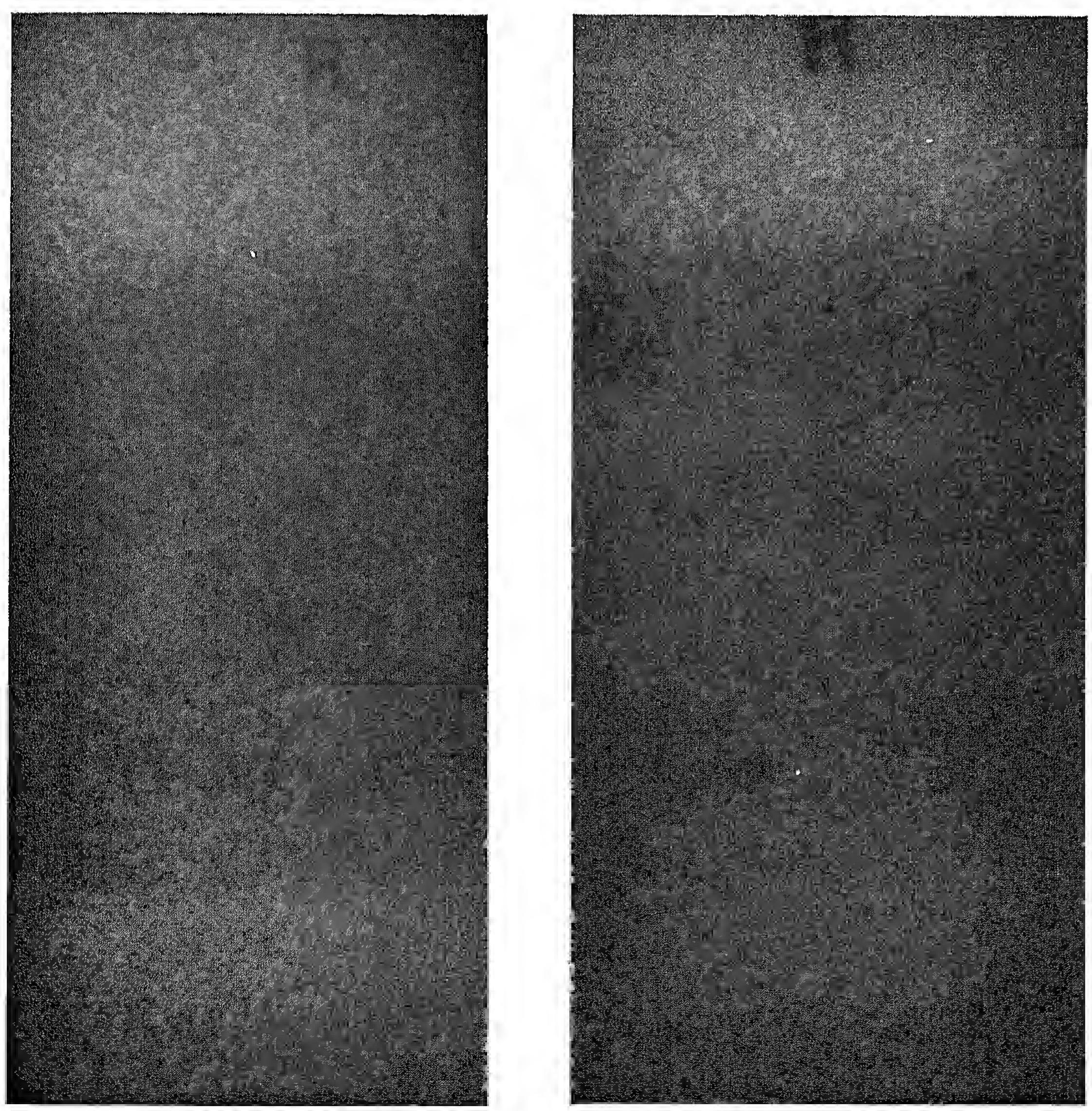
Of late years radium has been extensively used as a supplementary agent in radiological examination of metals. It has many advantages and it also has disadvantages. The early experimental work on this subject has already been reported.* Research in the use of

* V. E. Pullin: "Radium in Engineering Practice," *Proceedings of the Institution of Mechanical Engineers*, 1933, vol. 124, p. 305. V. E. Pullin: "The Radiographic Use of Radium," *Journal of the Royal Society of Arts*, 1934, vol. 82, p. 307.



Without grid diaphragm. With grid diaphragm.

**Fig. 7.**—Radiographs through a 2-in. section of a weld.



Without grid diaphragm. With grid diaphragm.

**Fig. 8.**—Radiographs of a $2\frac{1}{2}$-in. weld.

*Plate 8*

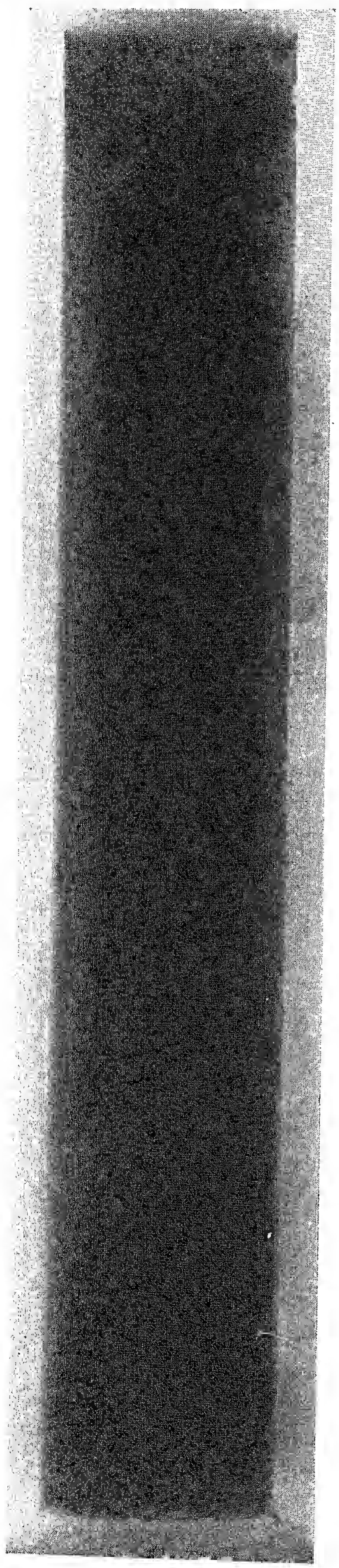


**Fig. 11.**—Radiograph of a heavy material inside a light alloy tube (without screens).

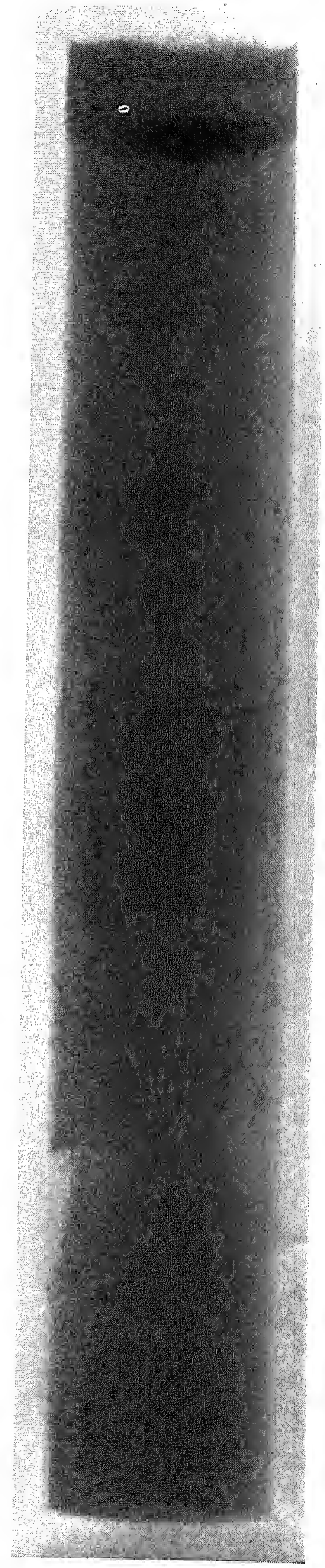
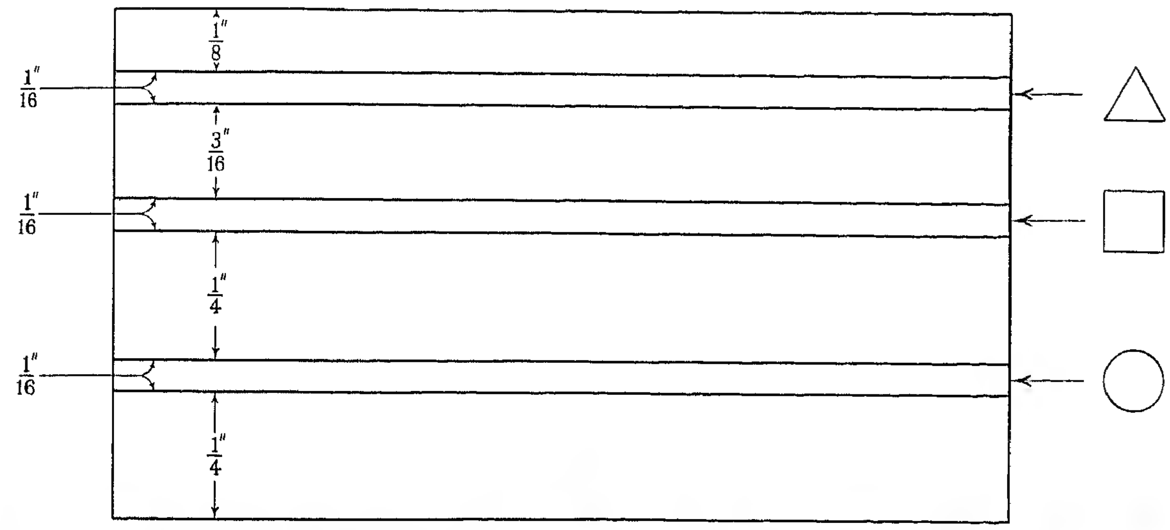
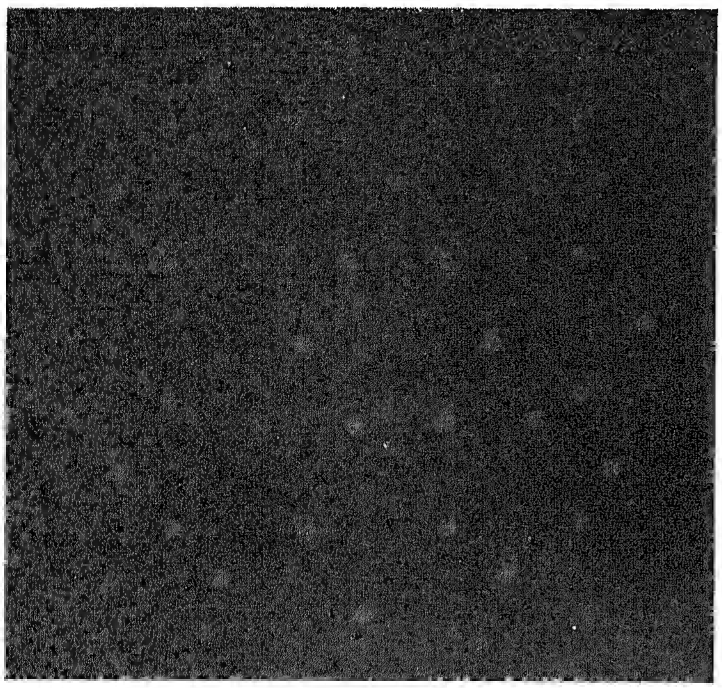


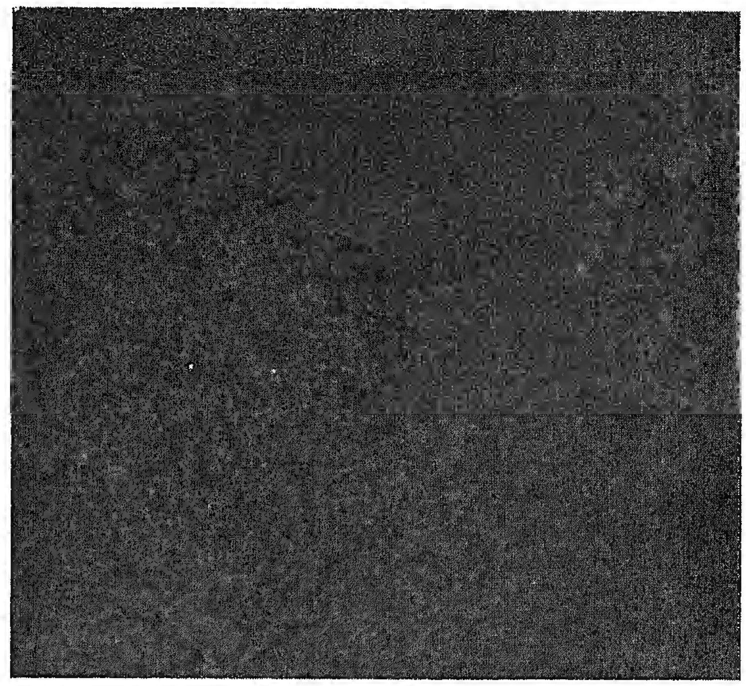
**Fig. 12.**—Radiograph of a heavy material inside a light alloy tube (with special film and lead screens).

*Plate 9*

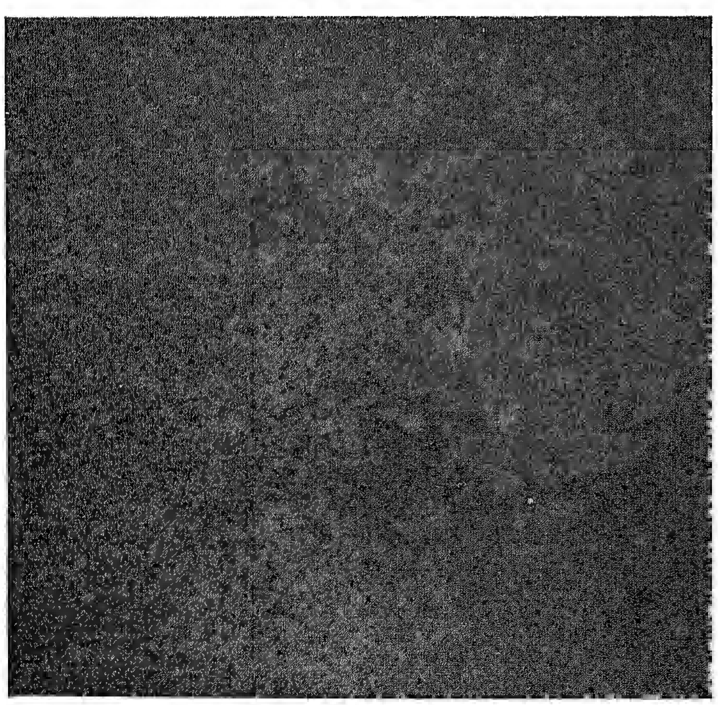


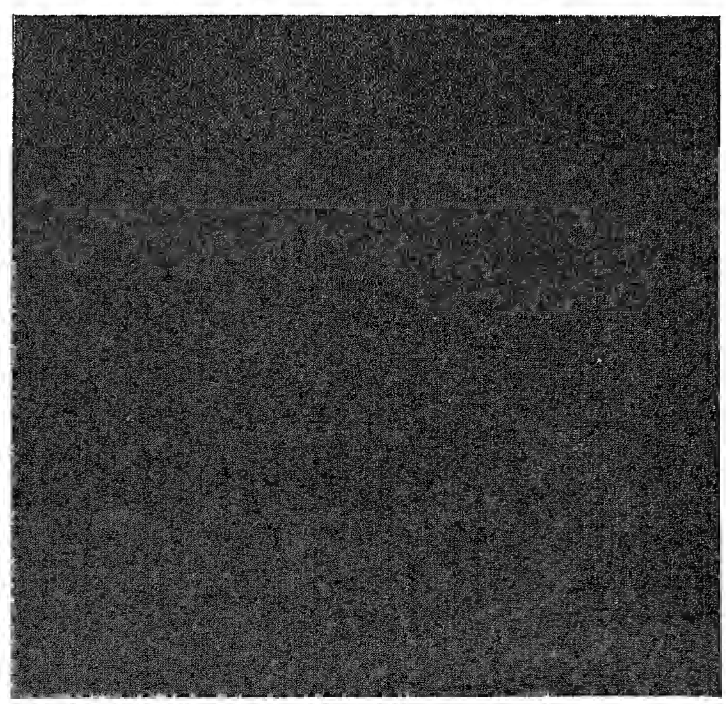
All spots showing.



Circle.



Triangle.



Square.

**Fig. 15**

*Plate 10*

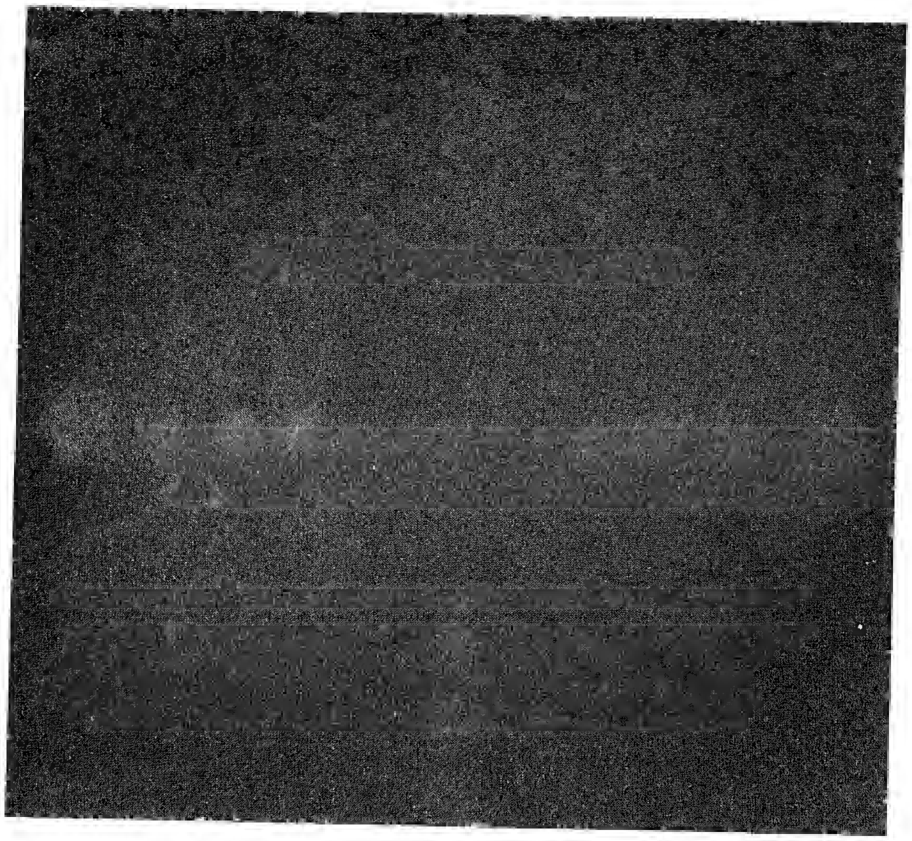


**Fig. 16.**—Penetration by radium of 6 in. of lead. Exposure 41 hours. Radium 9 in. from film. (Details of arrangement of holes in this specimen are shown in Fig. 17.)

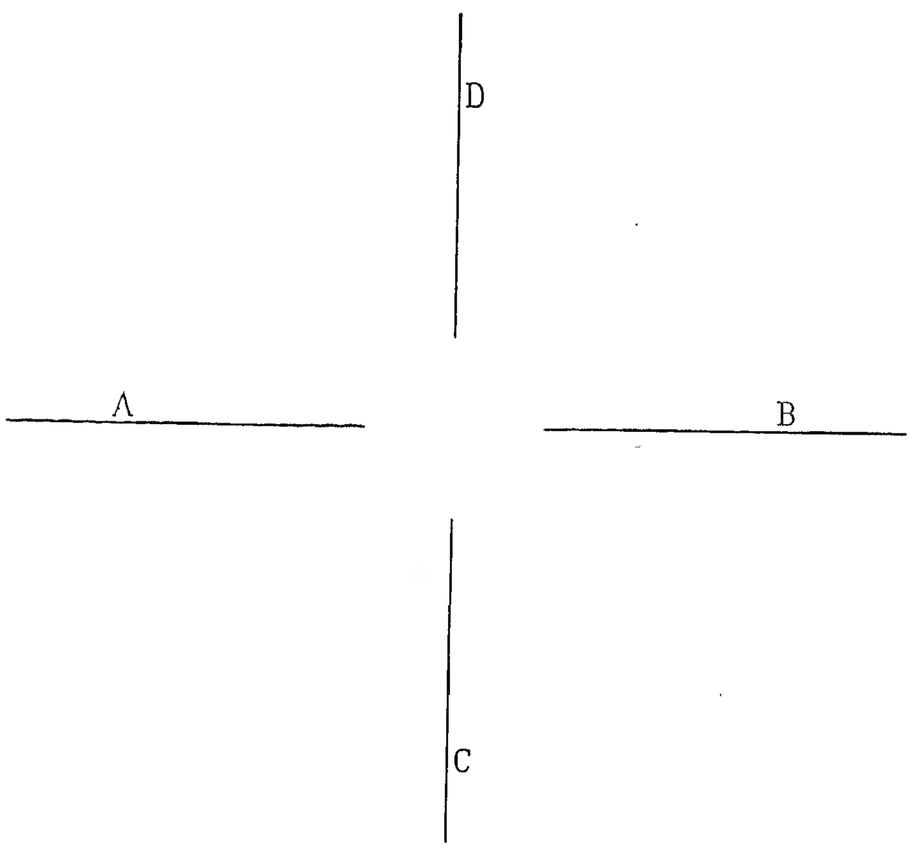



**Fig. 17.**—Diagrammatic key to Fig. 16.

Holes in Row A are drilled in $\frac{1}{8}$-in. sheet of lead placed next to film. All 6 holes are visible, and alternate holes are drilled conically.

Holes in Row B are also in $\frac{1}{8}$ in. of lead and are $\frac{3}{8}$ in. from film. The smallest hole ($\frac{1}{16}$ in. diameter) has now disappeared.

Holes in Row C are in $\frac{3}{16}$ in. of lead and are $\frac{1}{2}$ in. from the film. The smallest hole can be seen on the film but is too faint to reproduce.

Holes in Row D are also in $\frac{3}{16}$ in. of lead and are $1\frac{3}{4}$ in. from the film. The smallest hole is just visible on the film but is much too faint to reproduce.

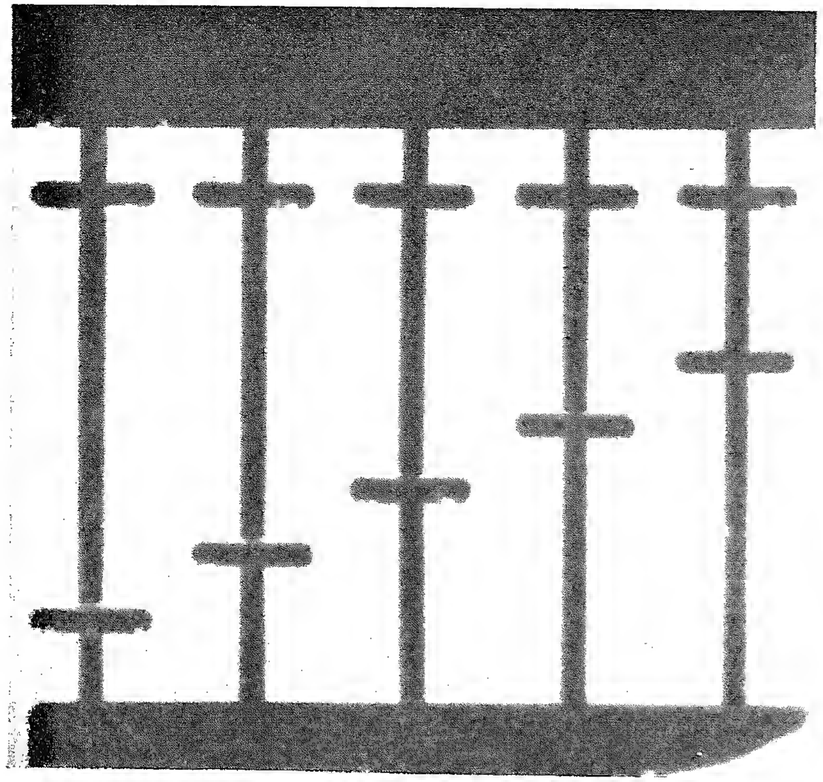


**Fig. 18.**—Radiograph by radium of battery grid (lead alloy), showing holes and cracks.

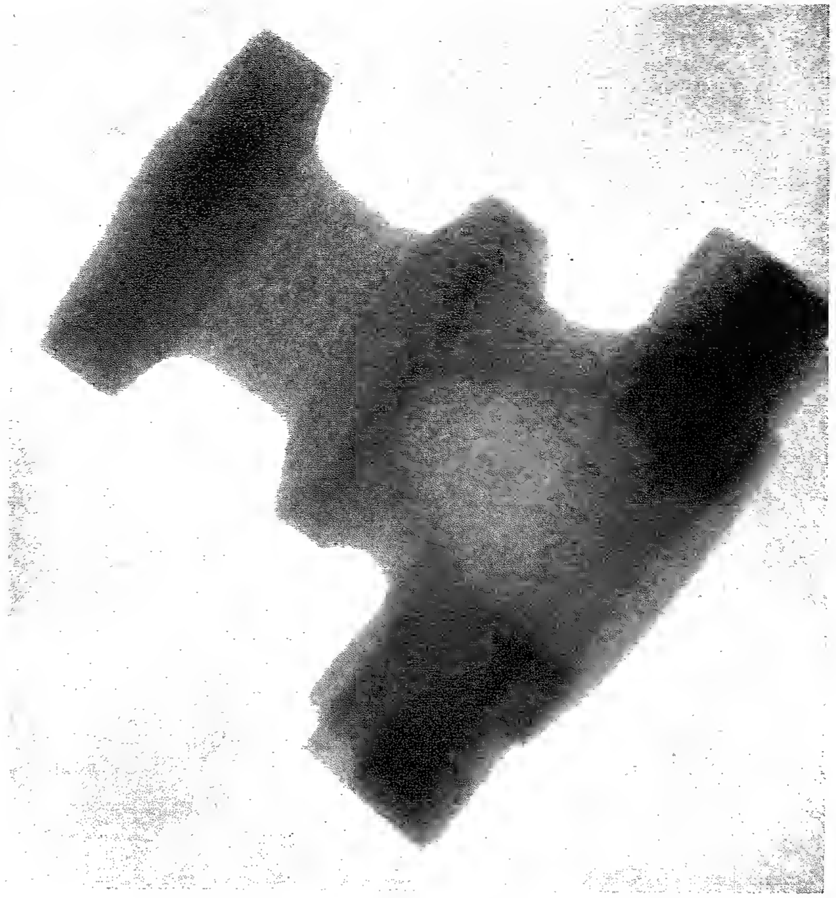


**Fig. 19.**—Radiograph by radium of $3\frac{1}{2}$-in. aluminium alloy casting, showing porosity. Exposure $1\frac{1}{2}$ hours at distance 28 in.

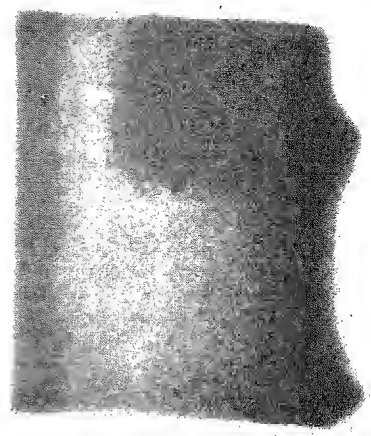


**Fig. 20.**—Radiograph by radium of copper embedded in lead alloy, showing porosity in the lead coating.

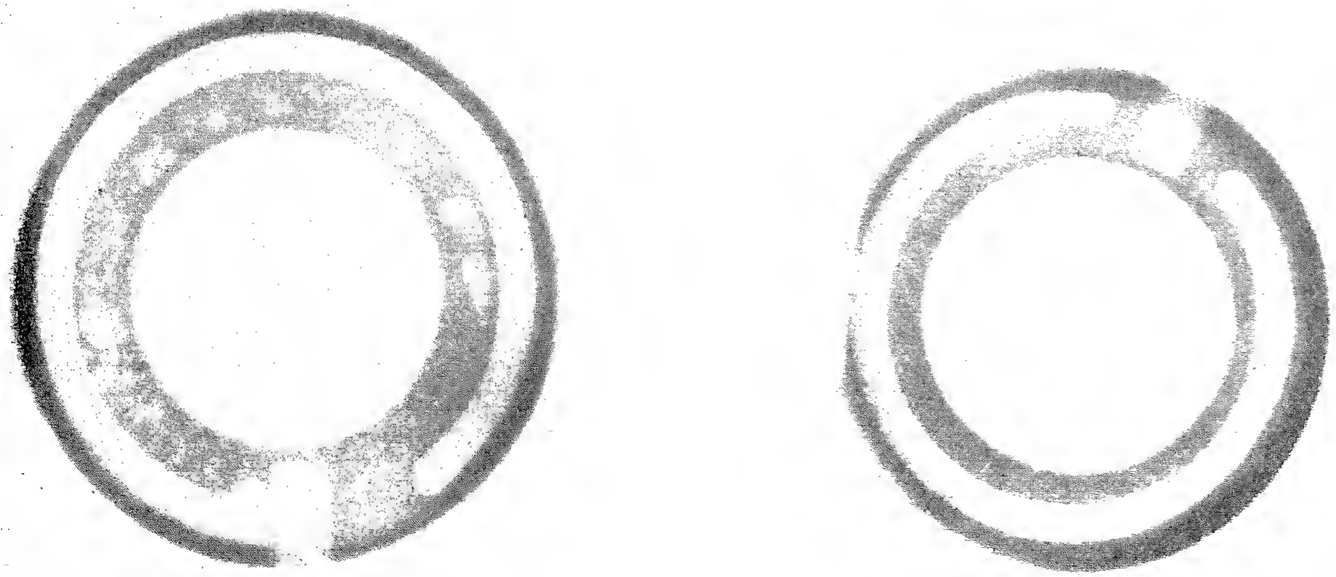


**Fig. 21.**—Radiograph by radium of zinc alloy rings, showing porosity.

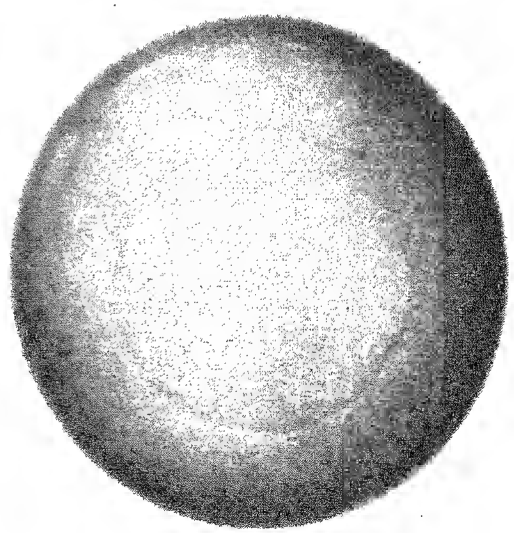


**Fig. 22.**—Radiograph by radium of a disc of extruded copper and brass.

*Plate 12*

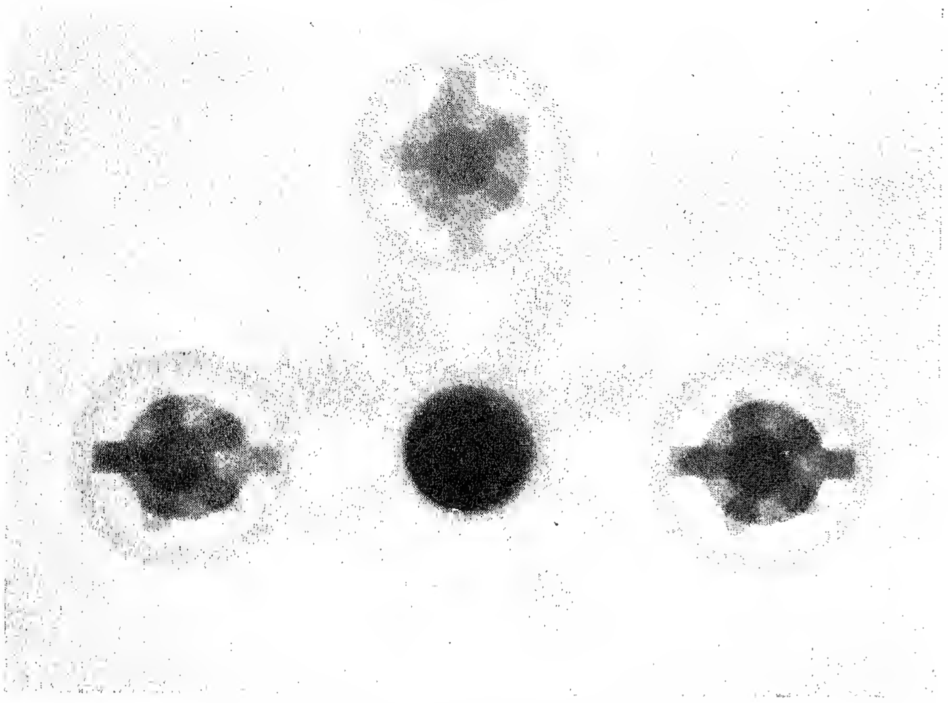


**Fig. 23.**—Radiograph by radium of experimental casting of 3 brass cogwheels. (Note fine detail.)

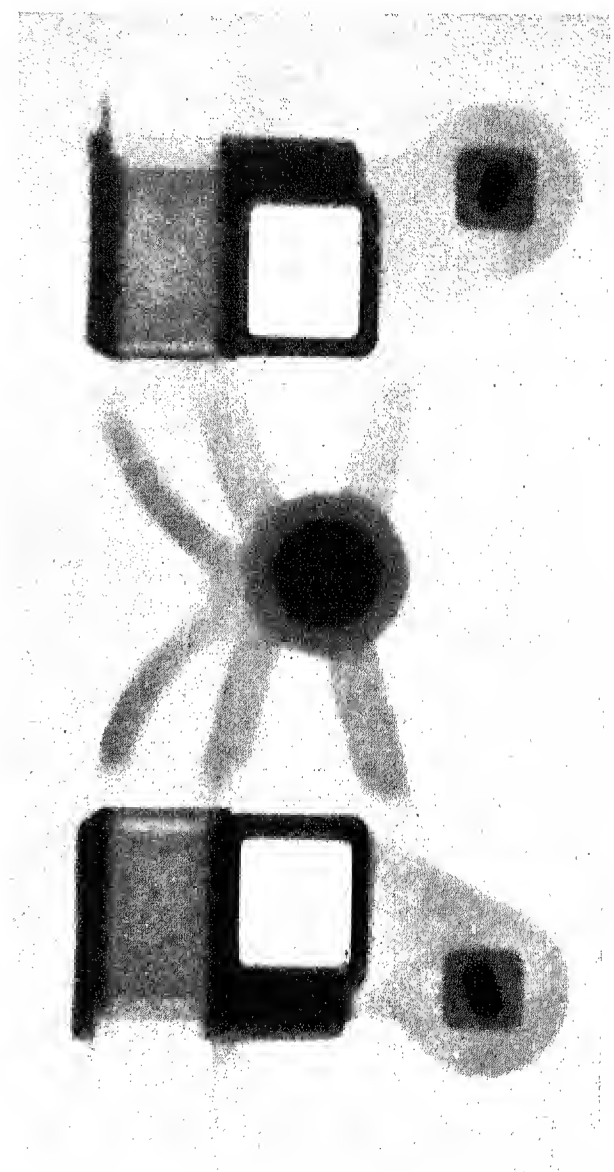


**Fig. 24.**—Radiograph by radium of aluminium bronze brush-holders. (Thickness of this specimen varies from $\frac{1}{8}$ in. to 2 in.)

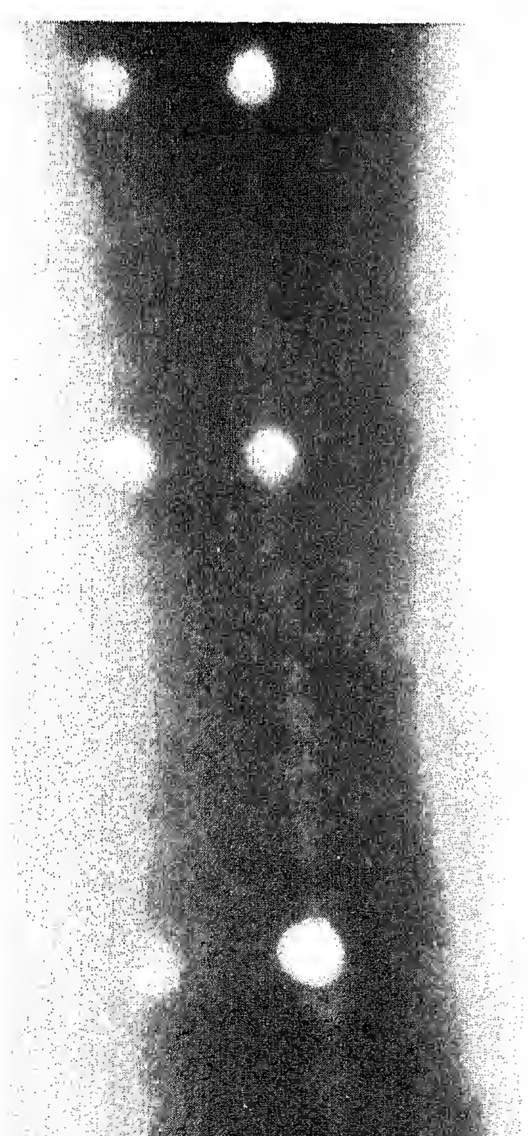


**Fig. 25.**—Radiograph by radium of a lead ingot 4 in. thick.

gamma-ray radiography carried out during the last few years has resulted in a very extended use of this technique in special cases. It has also served to show how many of the disadvantages originally experienced may be eliminated. In consequence of this work it is very probable that the use of radium in the inspection of engineering structures will become commonplace and popular as knowledge of its use and advantages extends. Its chief advantages must always be borne in mind when comparing its use with the use of X-rays. They are roughly as follows. Once the essentials of any particular exposure have been defined, radium requires no further manipulation—there is no ancillary apparatus. All that is required is the source of radiation, and the photographic film. Further, the radium may be used in very confined spaces, such as in the hold or engine-room of a ship, or it may be placed inside large castings or inside cylinders or pipes. Many articles may be placed in appropriate positions in the vicinity of the radium unit and exposed at one time. All these are practical advantages of great moment.

The Research Department's main source of gamma rays is in the form of a radium salt (242 milligrammes of radium bromide). This is permanently sealed in a glass container, and with it all the experimental work of the Department has been done and the exposure curves quoted in this paper have been prepared. The dimensions of the radium container are as follows: length, 1·18 in.; external diameter, 0·236 in.; wall thickness, 0·013 in.; net diameter of source, 0·21 in. This glass container is embedded in a steel capsule $1\frac{3}{4}$ in. long, 1 in. diameter, having a wall thickness of 2 to 3 mm. This is to cut off $\alpha$- and $\beta$-rays.

Fig. 16 (see Plate 10) illustrates two important points: (1) that the radiography of lead up to a thickness of 6 in. is possible (this penetration may be equated to 10 in. of steel); (2) that variations in thickness of 2 per cent in 6 in. of lead are easily detected in the radiograph.

There are one or two important points of technique which should be mentioned. It has been found advantageous in this work to use "focusing tunnels," each of which consists of a cylindrical block of lead 1 in. long and having an aperture $\frac{3}{8}$ in. in diameter. It is placed adjacent to the radium source. It would appear that the function of the tunnel is to project scatter into the main beam of rays and so increase contrast. The data given in the Table in col. 2 are the result of experiments made with this tunnel, and further work on its use is now in progress.

Intensifying screens are used in radium radiography as they are in X-ray work, and lead screens 3 mils thick have the following advantages: (1) Flexibility. (2) Adaptability (they can be cut into any required shape). (3) Absence of grain. (4) Thickness (frequently in radium radiography it is advantageous to expose a pack of, say, three films and several screens in order that the films may be viewed together as an aid to interpretation, the most common combination being two films and three lead screens).

In the case of salt screens for radium work it is necessary to employ screens having specially thick coatings, and when designed for use with two films such a screen should be coated on both sides. Further work is still called for on the question of salt screens for radium work, in order to determine the limiting permissible grain size.

One of the important disadvantages of the use of radium is the relatively poor definition that is obtainable. It should be remembered that the diameter of the source of gamma radiation used in the Research Department is 5 mm. If this source could be reduced to 1 mm. in diameter, the exposures could be made at $\frac{1}{5}$ of the present distance or alternatively in $\frac{1}{25}$ part of the time, and give the same definition. The bulk of exposures are made at a distance of 12 in., and it is not practicable to reduce this to any extent. The chief advantage of a reduced source-diameter would be an improvement in definition rather than a reduction in exposure time. At present it is possible by gamma radiography to obtain perfectly good definition in thin specimens, but in thicker specimens the required distance from source to film to achieve good definition may necessarily be so great as to involve uneconomical times of exposure; for example, for the radiography of a steel plate 1 in. in thickness the radium source should be something of the order of 50 in. from the film, requiring an exposure of 8 or 9 hours. With a radium source 1 mm. in diameter this same exposure could be made at a distance of 10 in. in something of the order of 20 minutes and give the same definition. An idea of the definition that is at present possible using gamma radiation with a large-diameter source (5 mm.) may be obtained from the radiographs shown in Figs. 16 to 25 (see Plates 10, 11, and 12). The quantity of radium used, of course, is a governing factor in the length of exposure, and it would seem that future radium radiography should be done by means of radium emanation rather than by the use of the more bulky salts of radium.

**Table**

| | Maximum thickness of added metal through which hole is visible | |
|---|---|---|
| | Without tunnel | With tunnel |
| | in. | in. |
| Crack 1 in. wide, $\frac{1}{16}$ in. deep .. | $\frac{6}{32}$ | $\frac{13}{32}$ |
| Hole $\frac{1}{16}$ in. diameter, $\frac{1}{16}$ in. deep | $\frac{7}{8}$ | $1\frac{3}{8}$ |
| Hole $\frac{1}{16}$ in. diameter, $\frac{1}{8}$ in. deep | $2\frac{3}{8}$ | $3\frac{7}{8}$ |

Research is at present being done on the use of radium emanation (radon) in this work. The use of the gas has many advantages over the use of a radium salt. In the first place, where investigations have to be made at distances from the main laboratory, the responsibility involved in carrying valuable radium salt from place to place is heavy and the lead container necessary for protective reasons increases the difficulty of transport very considerably. Radon has no intrinsic value. On the other hand, its use necessitates the installation of a complicated pumping system with a comparatively large amount of radium salt in permanent solution. If this pumping is efficiently carried out it means that a consistent supply of radium emanation is always avail-

able for use. The minimum amount of radium salt which should be kept in solution for practical purposes should, in the author's opinion, be 0·5 gramme.

A concentration of 100 millicuries per $mm^3$ can easily be obtained with radon. A source of 200 millicuries, therefore, could be used in the following ways: (1) in a sphere of diameter 1·6 mm., (2) in a cylinder 1 mm. in diameter and 2·5 mm. long, and (3) in a cylinder 0·5 mm. in diameter and 1 cm. long. Thus we can, by using emanation, choose the shape and diameter of our source to fit the particular problem under consideration, but the greatest advantage of all would appear to be that, by using emanation and thus achieving a much nearer approximation to a point source, definition can be increased to a very valuable extent. It will be seen from Fig. 26 that with our present source we are limited by its shape to the examination of a certain number of (say) shell placed in two arcs of a circle facing either end of the cylindrical radium source. If a spherical source were used it would obviously be possible to increase the number of shell exposed simultaneously by a very large factor. It is therefore reasonably safe to predict that with experience in the use of radium emanation for this work and its reduction to standard practice, the use of radium in engineering radiography will be very considerably extended.

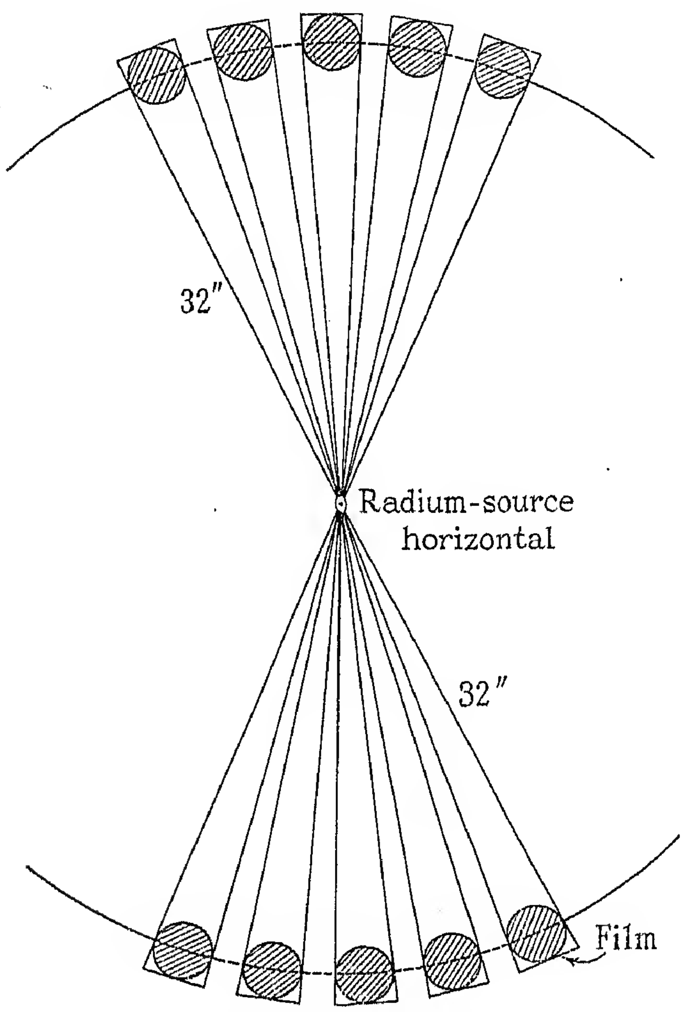



**Fig. 26.**—Sketch illustrating the examination of 10 shell simultaneously by a cylindrical radium source. If a spherical source were used 40 shell could be examined in one exposure.

Another advantage in all radium radiography is concerned with the effect of scatter as compared with its effect in X-ray radiography, the chief advantage being that with radium there is a comparative absence of high-angle scatter, such scatter as there is being chiefly concentrated in a forward direction; this has the general effect of enhancing the value of the incident beam. Experimental work has shown that internal scatter in radium radiography has comparatively little effect on photographic contrast. On the other hand, in lengthy exposures, care must be taken to shield the specimens from scattered radiation from surrounding objects such as the floor and walls, but this may be very largely reduced by the suitable interposition of thick lead sheets and similar screening devices. The advantage of the absence of high-angle scatter is most strikingly demonstrated in radium radiography by the ability of this method to produce radiographs of specimens which vary in thickness, specimens that it would be impossible to radiograph in one picture by X-rays owing to the effect of scatter. This phenomenon has been previously illustrated by the author in other papers.

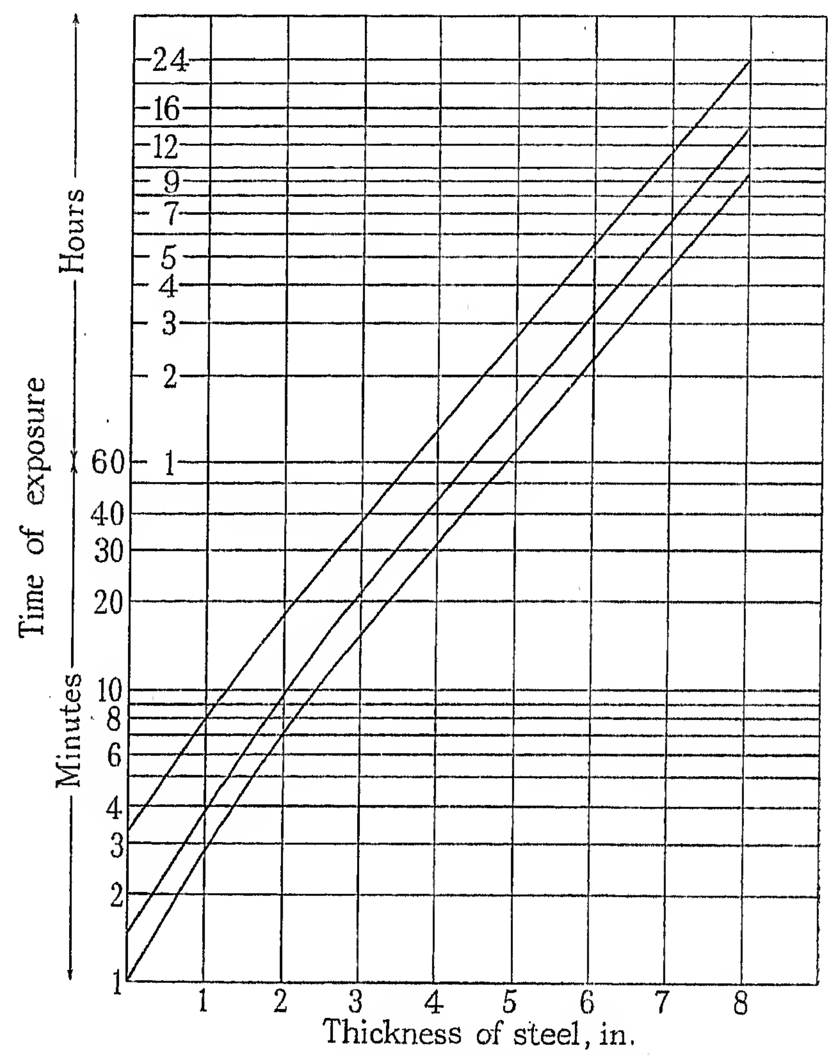



**Fig. 27.**—Exposure curves for steel, obtained with 242 mg. of radium at 9 in. from film, using two films, three lead screens, and full development.

The interpretation of radium radiographs is, in a sense, more difficult than the interpretation of X-ray radiographs. Very often, especially in thick specimens, shadows on the film are very faint and considerable experience is necessary to pick out vital shadows and also to distinguish them from possible photographic markings and film defects. Further, in thick specimens the technique of the examination is vitally important in that, if the film-to-source distance is not properly

calculated and maintained, or if the exposure is inaccurate, flaws which should appear may be missed. It should also be remembered that magnification of the

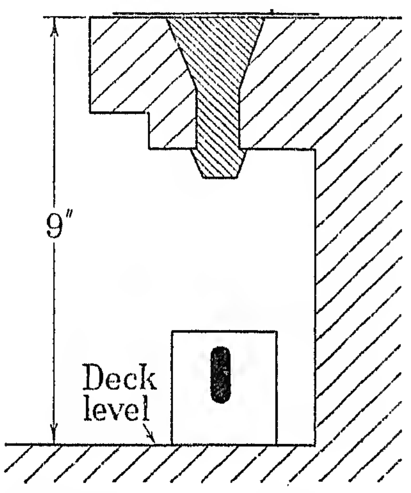



**Fig. 28.**—Sketch illustrating the examination by radium of the fit of rivets.

image in radium radiography, by virtue of the fact that thick specimens are so often radiographed, is a factor to be reckoned with in the interpretation. Fig. 27 is a set of exposure curves for steel, appropriate to the Research Department radium source. Figs. 28 to 31 illustrate the adaptability of radium in the examination of complicated structure. They are sketches made in the course of actual practical work.

## X-RAY CRYSTAL ANALYSIS

The fact that most solid materials are crystalline means that they lend themselves to special investigation by the method known as X-ray crystal analysis. This particular technique affords one of the most potent and striking weapons at the command of the physicist in the investigation of the constitution of matter generally, and it plays a most important part in the attack on many

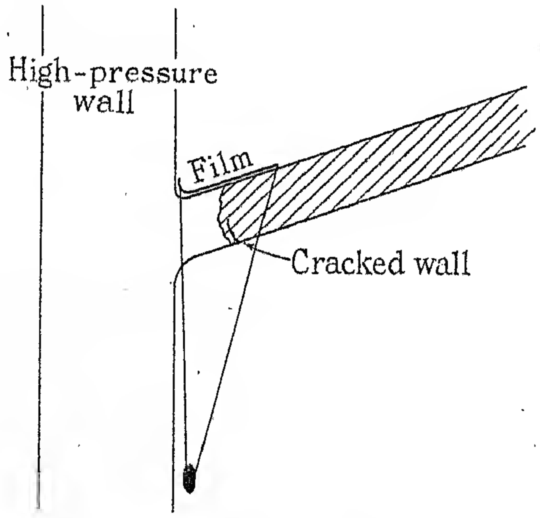



**Fig. 29.**—Sketch illustrating the use of radium in locating the end of a crack near a vital wall. (Note rays shot tangentially along wall.)

fundamental scientific problems. The method in its fullest expression is essentially a laboratory procedure and involves in its use expert physical experience and difficult mathematical analysis.

From the point of view of non-destructive testing of materials this technique is important, because at the present stage of its development it is possible to use

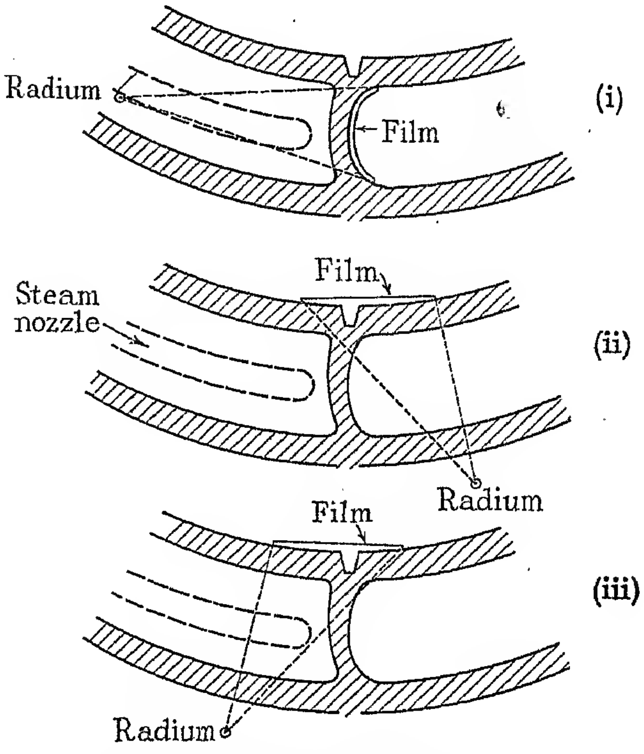



**Fig. 30.**—Sketch illustrating the use of radium in the examination of a turbine casting.

the method in a variety of ways of immediate practical utility. There are occasions when the method may be usefully employed in foundry and factory testing-rooms, and it is now possible to obtain from several of the large

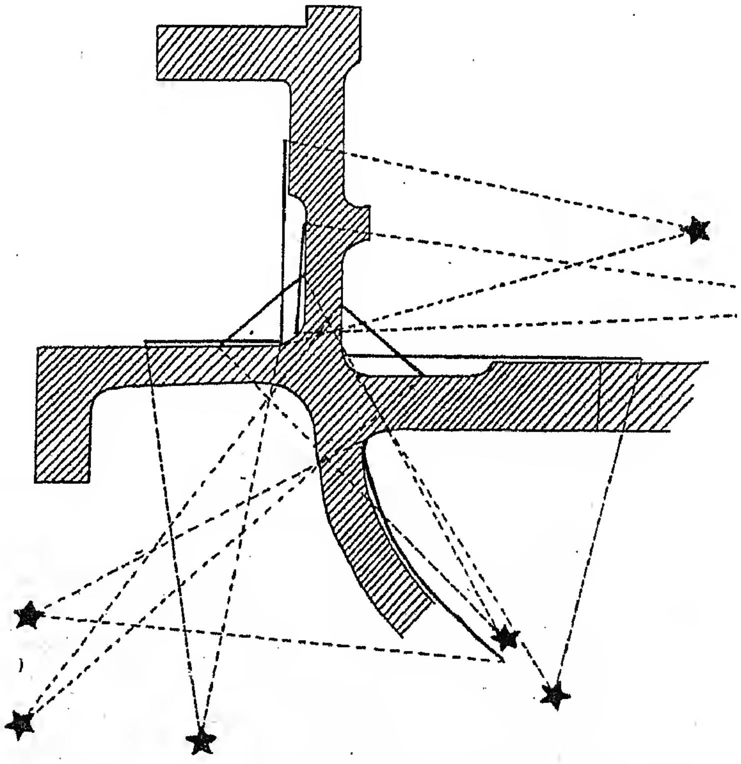


**Fig. 31.**—Sketch illustrating the adaptability of radium as a means of searching a complicated metal form from every possible angle.

X-ray equipment makers a robust and useful X-ray diffraction apparatus which requires very little experience on the part of the user and which does not demand a complicated laboratory setting.

The fundamental principle upon which X-ray crystal analysis depends is that atoms which constitute the lattice pattern in a crystalline material are separated from each other by a distance of the same order of magnitude as the wavelength of X-rays, i.e. some $10^{-8}$ cm. Thus the crystal lattice is capable of regular diffraction or reflection of a suitable beam of X-rays to produce a series of patterns (depending upon the atomic arrangement of the space lattice) on a photographic plate or film. The interpretation of these diffraction patterns, or X-ray spectra as they are called, enables us to deduce highly important information concerning the physical properties of the material under analysis. By modification of the original technique, it is now possible so to arrange the X-ray spectrum camera that spectra may be obtained from various points on the surface of a large structure, the rays being reflected back as a cone from a point on its surface to a photographic film carried in a special mounting on the camera itself, the resultant photographic pattern being in the form of a ring or rings. These patterns may be quickly interpreted to reveal the uniformity of crystalline structure (or lack of it) over the whole surface of an important casting, thus indicating, for example, possible places where the effect of heat treatment may vary. Permanent deformation of the space lattice is also to be deduced from a similar spectrum. The method has also been used to detect the incidence of corrosion, the early appearance of crystalline imperfection due to chemical attack being appreciable in the spectrogram. This rapid method may also be used to detect the presence of fibrous structure due to cold rolling or other reasons, and to examine electrodeposited metals to determine the orientation of the crystallites upon which the physical properties of the deposit so much depend. The reflection technique has been used by the author in the examination of a number of high-pressure valves to determine whether annealing had been adequate and uniform over the whole area. It has also been used to investigate the presence of residual stress in important fabricated engine parts.

For such work as that referred to above, which very properly may be described as non-destructive testing, the technique is simple and the exposures are comparatively short. The interpretation on broad but nevertheless highly informative lines is also a matter of simplicity. A pamphlet issued by the Department of Scientific and Industrial Research in 1934, entitled "The Industrial Application of X-ray Crystal Analysis," summarizes many interesting industrial applications of this method of test.

On the research side it is quite impossible even to outline the vast field for this method of investigation. For example, a complete study of any alloy system must include a very complete investigation by X-ray crystal analysis. Each phase has its own characteristic X-ray pattern, and the simultaneous presence of more than one phase is shown at once in this way. Similarly the transition points between the phases can be determined by X-rays with great accuracy. The effect of heat treatment upon alloys and indeed upon metals generally is fundamentally studied by this technique. H. J. Gough and W. A. Wood* in a recent study of alternating stress made valuable use of X-ray crystal analysis in their observations of the disintegration of crystallites associated with applied alternating stress, and there is little doubt that the whole future of metallurgical research will rest to a large extent upon the development and use of this branch of science.

## COMPLEMENTARY METHODS OF NON-DESTRUCTIVE TESTING

Among the many methods of investigation that have been developed in the Research Department perhaps the most generally useful has been the magnetic test. In this method, termed by the author the "ferrographic" test, the specimen is first magnetized and then sprayed with a suspension of finely divided iron in a suitable liquid. A series of specially shaped electromagnets have been constructed with adjustable pole-pieces, and this apparatus has been fitted into portable cases to facilitate transport. By the aid of these magnets small sections of structures of complicated shape may be easily magnetized and examined. In the case of cylinders such as gun tubes a flash magnetization method due to A. G. Warren† is used. A cable is threaded through the cylinder and a heavy current is momentarily passed through it, resulting in the cylindrical magnetization of the whole specimen. A conical spray is then introduced into the bore on a telescopic tube and the iron suspension is pumped evenly over the entire surface. Subsequently the conical spray is replaced by an illuminated mirror, and by its aid the inner surface of the cylinder is carefully examined for lines or spots of iron concentration indicating defects in the surface or the immediate sub-surface.

Other methods have also been found to have valuable applications in special cases. For example, a modified impedance method of test, also due to A. G. Warren, has been found of great use in investigating the dimensions of flaws and the depths of cracks previously detected by radiography. In a similar way electrical conductivity methods have also been developed for use in appropriate cases.

## ACKNOWLEDGMENTS

It is a very great pleasure to acknowledge the valuable work on all aspects of non-destructive testing which has been done by the author's colleagues in the Radiological Directorate of the Research Department, Woolwich, especially Mr. W. J. Wiltshire's work on the general technique of X-ray radiography and that of Mr. C. Croxson on the use of radium. The author's thanks are due to these gentlemen for their assistance in the preparation of this paper.

The author also wishes gratefully to record the permission of the Ordnance Committee to publish this paper.

* *Proceedings of the Royal Society*, A, 1938, vol. 165, p. 358.
† *Engineering*, 1935, vol. 140, p. 353.

[The discussion on this paper will be found on page 580.]

# INDUSTRIAL RADIOGRAPHY ON THE CONTINENT OF EUROPE

By Ir. J. E. de GRAAF.*

(*Paper first received* 24*th September*, 1938, *and in revised form* 20*th February*, 1939; *read at a meeting arranged by the* JOINT COMMITTEE ON MATERIALS AND THEIR TESTING, 25*th November*, 1938.)

## INTRODUCTION

In the first phase of industrial radiography, which commenced about 1920, its possibilities and methods were investigated† in universities and works laboratories, and its use in the shops was started. This phase is characterized technically by the development of apparatus which could safely be placed in the hands of people unskilled in physics, the requirements of shock-proof, ray-proof, and fool-proof construction being satisfied.

In the second phase, which still continues, special requirements in regard to improved photographic quality and lower cost are being developed, and are more or less satisfied. Quantitative researches are being undertaken to establish a basis for rational requirements or for compromises between contradictory demands.

## SENSITIVITY AND COST

The required sensitivity (which measures the quality of the photograph or the fluorescent picture by the smallest visible thickness difference) and the acceptable cost, vary with different individuals and in different countries. Although, of course, the cost should be as small as possible everywhere, the requirements for sensitivity seem to be generally higher in Europe than in America. There penetrameters are used which consist of strips, and a thickness difference of 2 % should be visible according to the A.S.M.E. Boiler Construction Code. In Europe it is realized that the visibility of most flaws depends on contrast and lack of definition, the latter having only a slight influence on the sensitivity measured with the strip penetrameter. Therefore wires are used in Europe as test objects to standardize picture quality. This requirement calls for lower voltages and higher cost, but most European users accept this as fully justified. For although experiment may sometimes show that if a flaw is invisible this is sufficient to ensure mechanical safety, experience with micro-pores in certain light metals proves that even very small flaws can have a large influence. Of course when only flat flaws are to be expected the strip penetrameter will suffice. The need for test objects approximating more to the case of porosity is only seldom felt, as the visibility of wires and of balls varies in the same way with the voltage and with the thickness of the object.‡ Thus standardization of picture quality can be attained equally well with wires. Wire sensitivity is not a sufficient measure for porosity delineation when the lack of definition in different directions differs very much, as happens when the projection of the focal spot is very long and narrow. Then it is advisable to lay the wires parallel to the major direction of the flaws, e.g. parallel to the seam in the case of welds. In special cases where the wire standard is insufficient, the use of the ball standard could be specified, as even without the influence of poor definition the diameter of the just-visible ball (pore) is about twice as large as the diameter of the just-visible wire.

Reduction of cost usually implies reduction of time per job. As this time is composed of a radiating time and a positioning time, it can be reduced without decreasing the sensitivity when the positioning time can be reduced. With screening or photography of small pieces made in mass this can be achieved by the use of suitable conveyors; but with photography of large castings and structures the construction of the apparatus and tube especially can greatly influence the positioning time. In such cases, transport is frequent and a small weight per part helps effectively in reducing the time, even if the number of parts is increased. The transport of the generator (the heaviest part) can be reduced by the use of long cables, so that only the tube need be moved. The construction of the tube is also important, as the use of one cable instead of two facilitates movement. Moreover, new types of tube allow of easier positioning by placing the focal spot inside a hollow workpiece and the film on the outside, instead of the reverse.

Decreasing the exposure time by means of smaller photographic density, higher voltages and currents, larger irradiated fields, smaller distances, and lower filtration, often means decreasing the sensitivity.

The photographic film shows a maximum gradation and therefore maximum sensitivity at a density of about 1–1½, which is used more and more since sufficiently powerful viewing lanterns of a brightness of, for example, 1 000 candles per m² are available (previously densities of 0·5 and 0·7 were advocated).

The influence of voltage and field diameter on contrast is shown in Fig. 1. The same contrast can be obtained with a field diameter of 90 mm. and a voltage of 70 kV, and with a field diameter of 30 mm. and 120 kV when the basic density (obtained in 120 and 15 seconds respectively) is the same. This example stresses the necessity of using the smallest possible irradiated fields. Another example of sensitivity gained through good photographic technique is the application of filters of heavy metals for absorbing scattered radiation.†

The permissible current at a given focus is limited by

* N. V. PHILIPS, Gloeilampenfabrieken, Holland.

† V. E. PULLIN: *Electrician*, 1925, vol. 95, p. 614.

‡ E. A. W. MÜLLER and W. E. SCHMID: *Zeitschri für Metallkunde*, 1936, vol. 17, p. 190.

† R. BERTHOLD: *Archiv für das Eisenhüttenwesen*, 1934–35, vol. 8, p. 21.

the roughening of the focus, which reduces the output by increased absorption. This, in combination with a life of, say, 2 000 hours, limits the focal temperature, which depends* on the method of cooling (water-cooling being best), the anode material (a high heat conductivity being desirable), its thickness, and the focal dimensions.

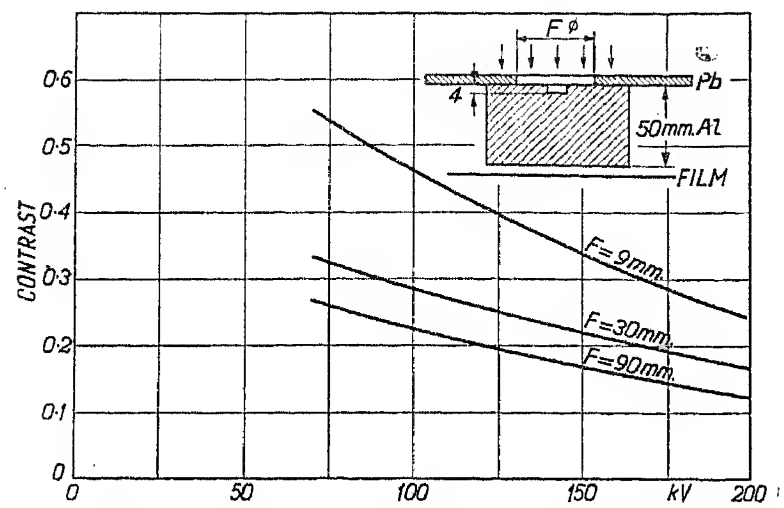



**Fig. 1.**—The influence of tube voltage and field diameter ($F$) on the contrast with constant photographic density.

With a water-cooled anode the specific load increases with decreasing focal dimensions, owing to the lateral flow of heat, which makes the effective cooling surface larger than the focus. This is indicated in Fig. 2, where the total load permissible on a circular focus is shown by the full line. For $f = 1$ mm. this load has double the value of the dotted line, which is derived in proportion to the focal area from the permissible load for $f = 4$ mm. This is an argument in favour of smaller foci in those cases where the focus film-distance (f.f.d.)

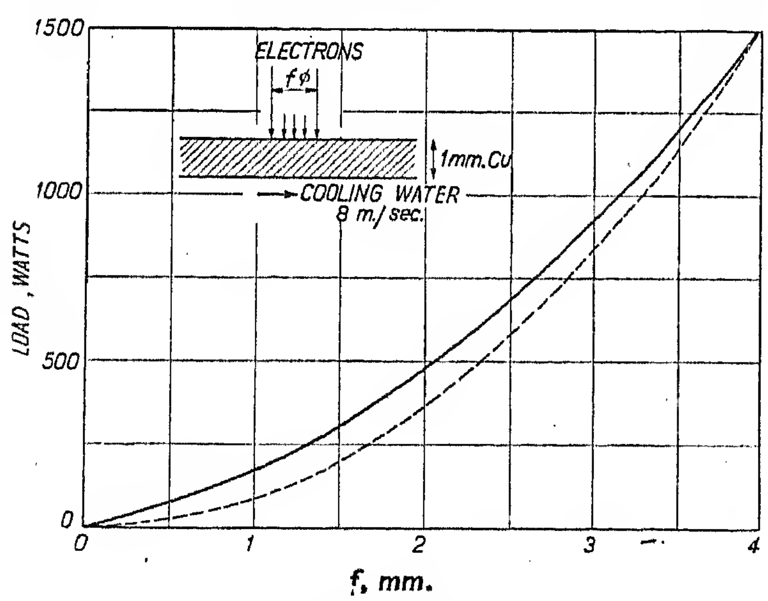



**Fig. 2.**—The full line shows the total load permissible on a homogeneously bombarded circular focal spot ($f$ mm. diameter) on a copper anode cooled by tap water. For a tungsten anode the permissible load is 2 or 3 times the load shown.

can be made small. When, on the other hand, a certain focus is required there is an optimum anode thickness, for the speed of the cooling water limits the maximum specific cooling capacity because the water should not boil, and with increasing anode thickness the lateral flow of heat increases the cooling serface. Thus it is necessary to increase the specific load with increasing thickness in order to keep the cooling capacity at its tolerable maximum. At the same time, however, the focal temperature rises because a larger temperature difference is necessary in order to convey the heat. When, therefore, with increasing thickness and load the maximum focus temperature is reached, the optimum thickness is also reached, because with larger thicknesses the load must decrease in order to keep the focal temperature at its tolerable maximum.

A smaller f.f.d. reduces also the exposure time. This distance is, in combination with a given focus, limited by distortion of the picture and by poor definition. Fig. 3 shows the relation between the diameter $\delta$ of the just-visible ball and the geometrical blurr, i.e. the width of the penumbra caused by the finite width of the focal

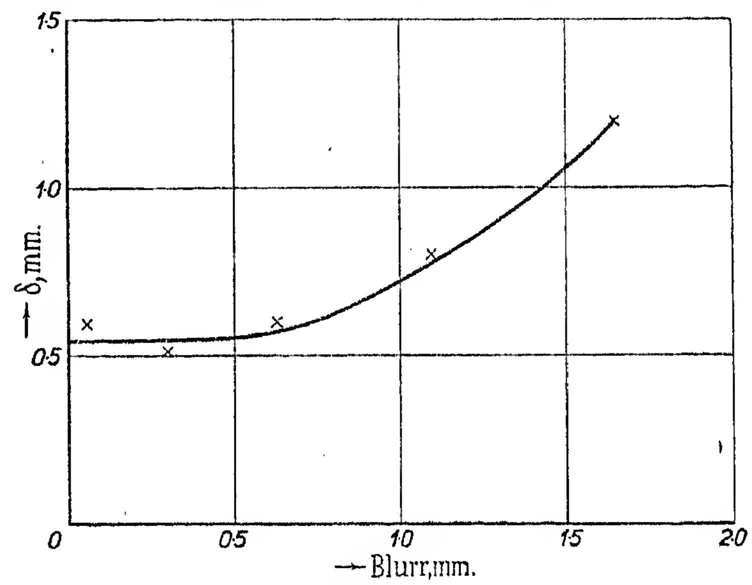



**Fig. 3**

spot. When the blurr is small, the diameter $\delta$ remains constant and is only determined by the contrast. At a certain value of the blurr the diameter $\delta$ increases rapidly, and it is found that the ratio between this value and the $\delta$ at low blurr varies only a little with the thickness of the wall of the object on which the balls or wires lie. With wires the ratio is between 1 and 2, with balls between $\frac{1}{2}$ and unity. With a certain width of the focal spot there is thus a minimum f.f.d. When the exposure time has to be shortened, it is always better to increase the tension than to decrease the f.f.d. below this minimum value, as in the latter case the loss of sensitivity is far greater.

In some cases, however, an optimum f.f.d. much larger than this minimum value can be calculated to require the lowest total time for radiography with a given tube, potential, and apparatus, because with increasing f.f.d. the number of exposures and thus the total positioning time are reduced, while the exposure time increases. So, for pipes, even for those of large diameter such as boilers, it is usually better to take the whole seam from the centre in one long exposure with a tube radiating in all directions, than to take it part for part with shorter exposures. For straight seams (longitudinal seams of boilers) also an optimum f.f.d. can be calculated, usually near 50 to 80 cm., depending on positioning time and exposure data. In

* J. E. de Graaf and W. J. Oosterkamp: *Journal of Scientific Instruments,* 1938, vol. 15, p. 293.

such cases the focal dimensions can be large and, consequently, high currents can be used. But when inspecting welds in small steam pipes the f.f.d. is limited and the tolerable focal diameter is a few mm.

Low filtration decreases the exposure time. It is not so important, however, for photography, as this method is rarely applied to steel thinner than 8 mm., work of this kind being seldom sufficiently important. Thus photography of steel only rarely requires less than about 80 kV, and 1 mm. of copper is tolerable as inherent filtration. For fluoroscopy, however, the inherent filtration in the tube should be as small as is compatible with the air pressure on the window, and eventually with bombardment by electrons. Fig. 4 shows the influence of a copper filter. Although the change of sensitivity may seem small, its influence can be large, as many flaws are only just visible (Müller and Schmid, *loc. cit.*).

With fluoroscopy and with the electric methods (ionization chambers and Geiger counters) the radiating

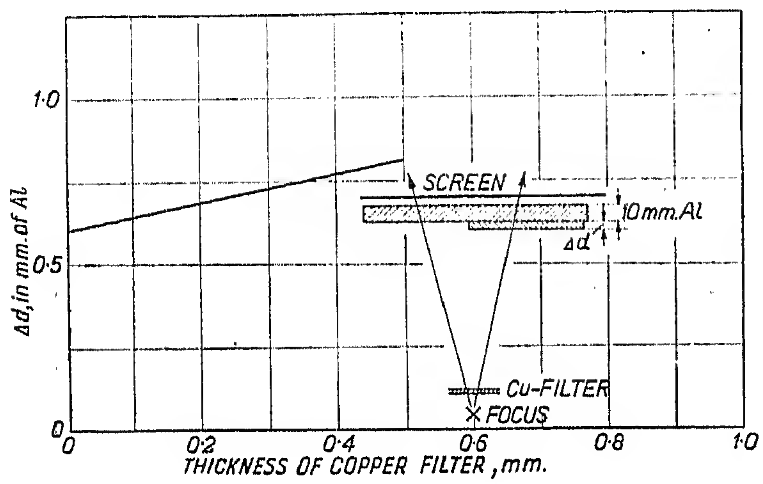



**Fig. 4.**—The influence of the copper filter of the X-ray tube on the fluoroscopic sensitivity, which is measured by the smallest thickness difference ($\Delta d$) visible. For each filter thickness the optimum voltage was determined and the sensitivity taken at this voltage (75 to 100 kV; 4 mA).

time necessary for the detection of a flaw is correlated with the sensitivity.

With fluoroscopy a flaw is found more quickly when the sensitivity is high. A high sensitivity requires large currents, which are in many cases tolerable even at the cost of a relatively large focal spot, because sharpness is often of secondary importance as the large grain of the screen and the inter-reflection of light in the sensitive layer* introduce a great lack of definition.

With ionization chambers† or Geiger counters‡ the speed of inspection and the sensitivity are correlated. For the first kind of apparatus it has been shown† that in the most sensitive adjustment the volume of the flaw is the critical quantity. The smallest volume which the apparatus detects (a measure of the sensitivity) is nearly proportional to the speed at which the flaw passes the chambers, provided that the time required to pass is sufficiently short in comparison with the time-constant of the amplifier.

* R. Berthold, N. Riehl, and O. Vaupel: *Zeitschrift für Metallkunde*, 1935, vol. 27, p. 63.

† J. E. de Graaf and J. H. van der Tuuk (*Philips Technical Review*, 1938, vol. 3, p. 228) traced with ionization chambers automatically the presence of flaws larger than 3 mm. in 10 mm. of steel.

‡ A. Trost (*Stahl und Eisen*, 1938, vol. 58, p. 668) checked automatically with Geiger counters the thickness of rolled steel tubes within a few per cent.

Fluorescent screens, ionization chambers, and Geiger counters, all show an optimum voltage, depending on the tube current. With fluorescent screens this is due to increasing sensitivity of the eye with increasing screen brightness so long as the brightness is small, and to decreasing contrast in the radiation with increasing voltage. Calculation and experiment show that this optimum is approximately the voltage for which the thickness of the metal under examination is 3 or 4 times the half-value layer. For ionization chambers and Geiger counters the optimum voltage is of the same order, viz.

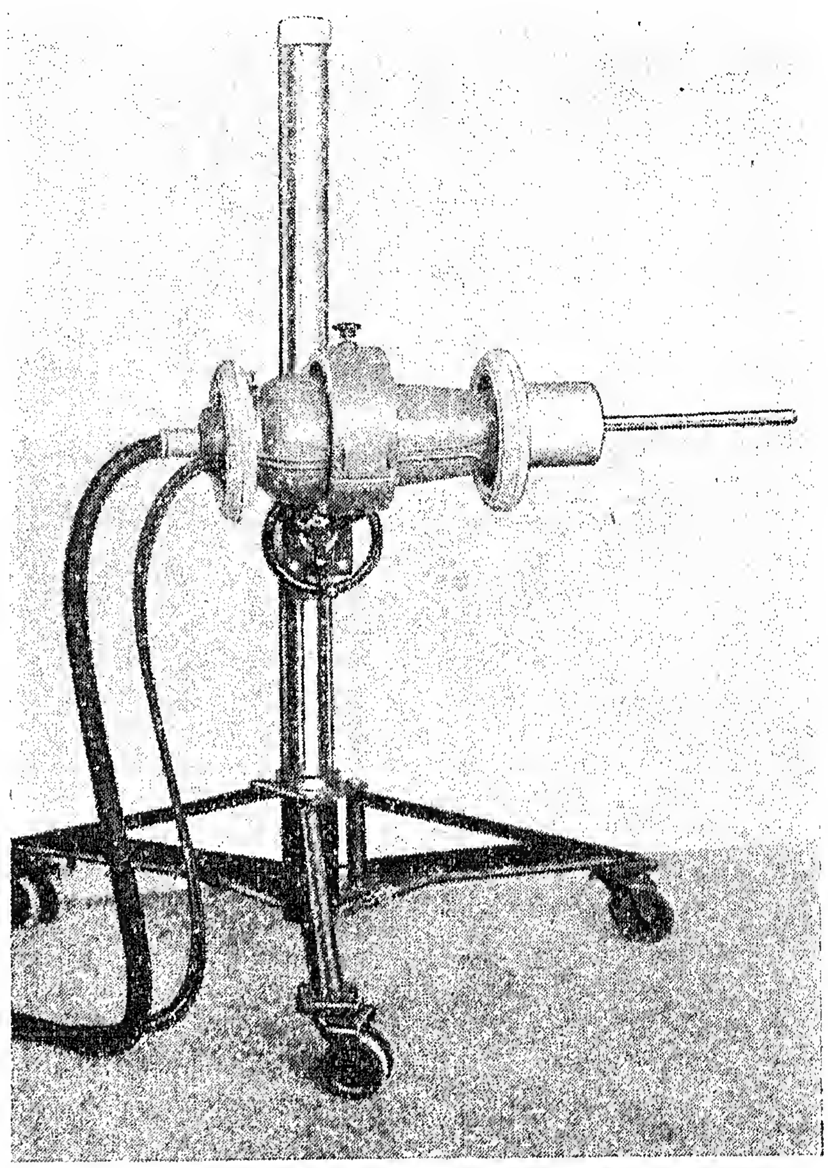


**Fig. 5.**—Single-cable tube for 150 kV with the focus at the end of the tubular projection ("oxtail tube"). Focusing of the electron beam is accomplished by an electric coil. Form, dimensions, and load of the focus, depend on the application.

where the thickness of the metal under test is 2 or 3 times the half-value layer. Fortunately the optima are not very pronounced.

## SOME APPLICATIONS AND THE APPARATUS REQUIRED

As characteristic of the many and varying applications, the photographic inspection of welds and castings, and the fluoroscopy of light metals, will now be discussed.

As welds can show very fine flaws, the wire sensitivity is always used on the Continent of Europe. The higher cost involved is usually acceptable as many welded structures are important.

When boiler welds are inspected in the shop, a truck can be used for transport, so that small weight and long

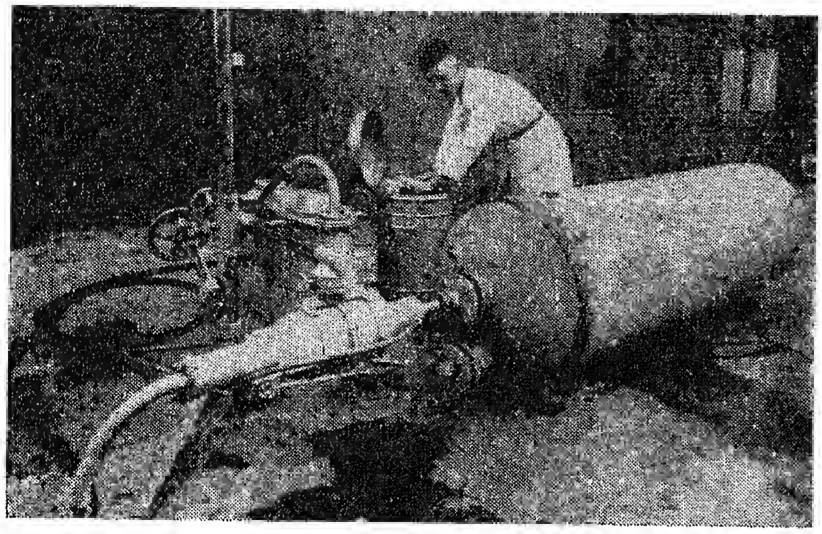


Fig. 6.—Use of long-anode tube for photography of the circumferential head seam of a steel vessel.

cables are not so important as when the boiler is inspected in the boiler house.

Circumferential seams are best examined with a tube placed inside the boiler, in which case a single-cable tube is very desirable. When the tube radiates in all directions of a plane, the seam can be taken in one exposure, which reduces the total time to a small part of that needed with an older tube radiating within a narrow cone. Even if the seam is quadrangular as in fire-boxes, this technique is applicable by the use of intensifying screens of different sensitivity to compensate for the differences of X-ray intensity on different parts. A long anode, such as that illustrated in Fig. 5, is not always necessary for boilers. However, when welded flanges of steam pipes or welded head attachments are inspected, such an anode is essential to bring the focus in the

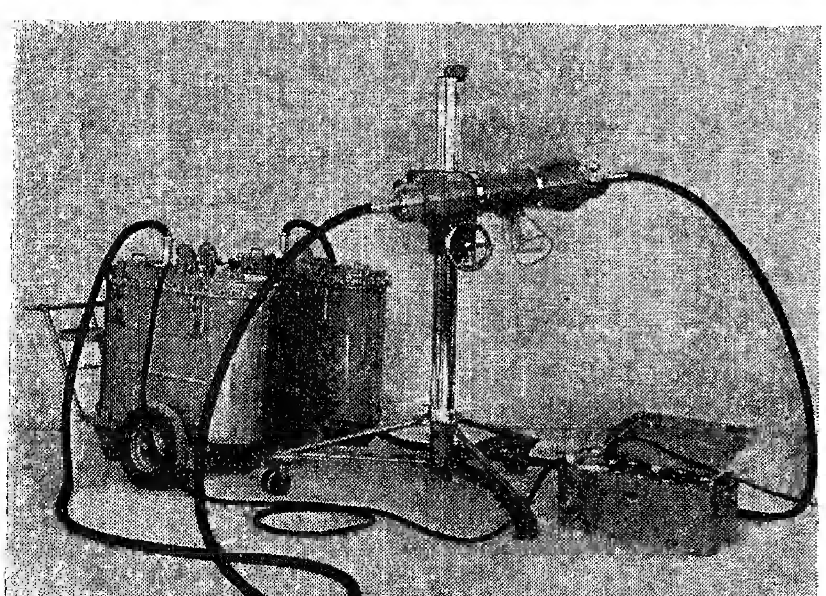


Fig. 7.—Subdivided portable apparatus for 300 kV. Each half can be used for a 150-kV single-cable tube.

centre of the seam (see Fig. 6). For the photographic work the filter need not be particularly small. The focus of the oxtail tube is usually limited to a few mm.

For very large thicknesses up to 100 mm., requiring voltages of 300 kV, completely protected and yet flexible

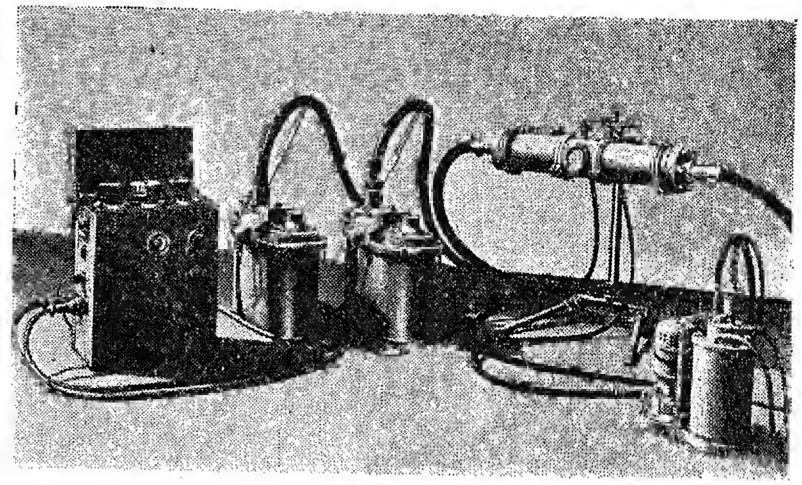


Fig. 8.—Completely protected apparatus for 200 kV, 8 mA, subdivided for portability.

apparatus (Fig. 7) is in use. For intermediate thicknesses equally protected and portable apparatus is available for 200 and 250 kV (Fig. 8).

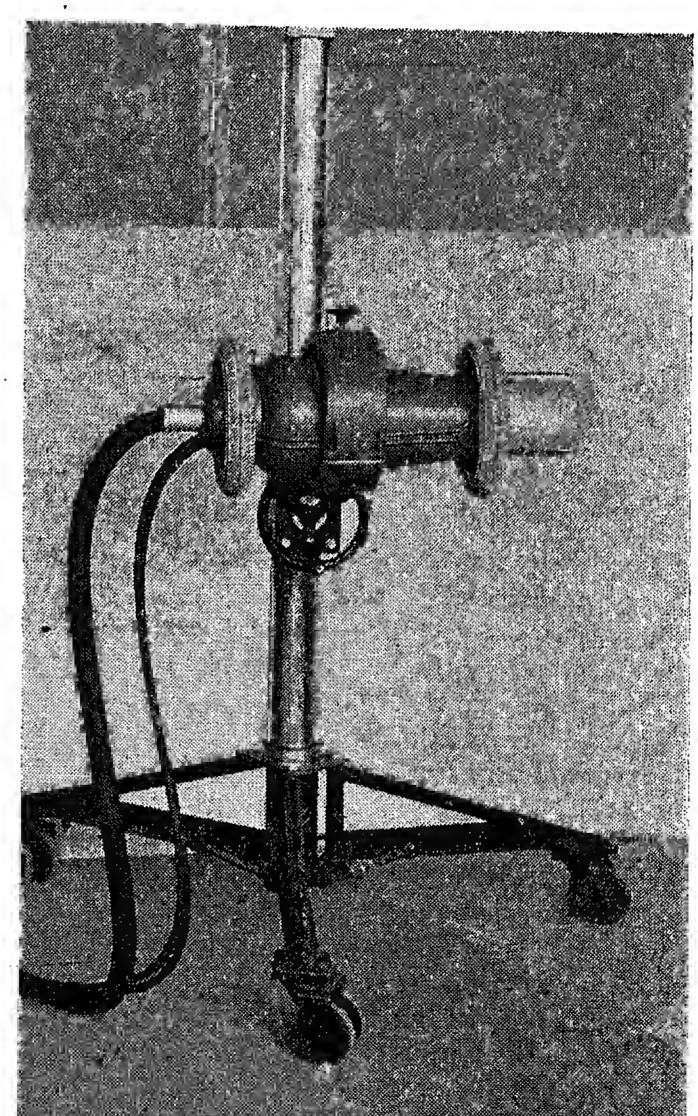


Fig. 9.—Single-cable tube for 150 kV with the earthed anode at its end. No electric coil is needed. The load on the 5-mm. square focus is 20 mA at 150 kV.

Welds in structures, ships, etc., are often inspected on the site. Portability is now essential for low cost, as transport has mainly to be done by hand. If the total

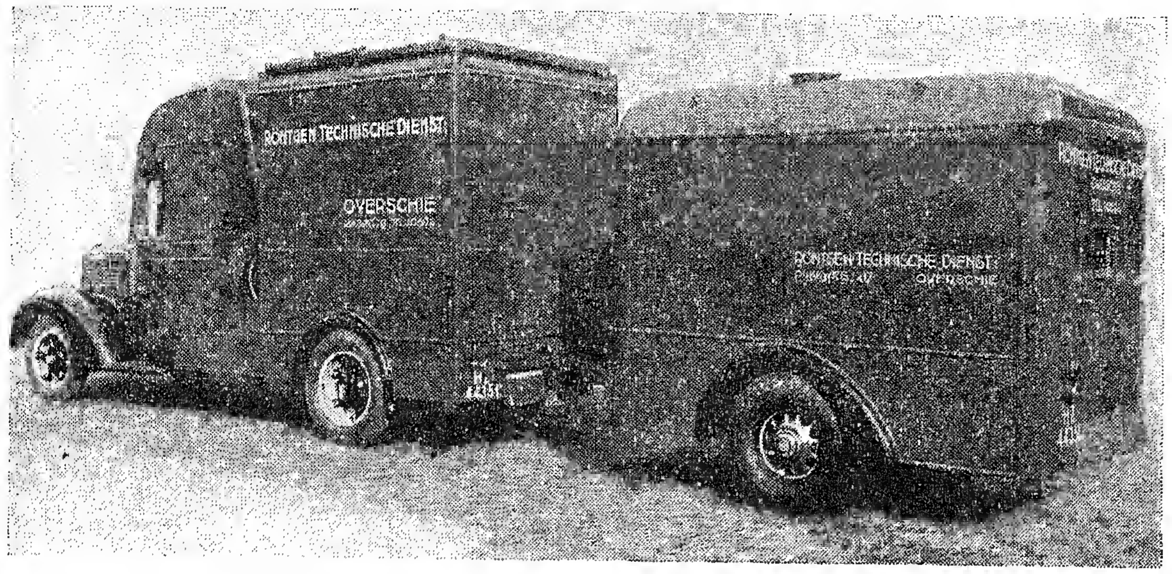



**Fig. 10.**—Motor-car and trailer containing X-ray apparatus, dark-room, etc., for the inspection of work dispersed throughout the country. (Reproduced by the courtesy of Mr. van Ouwerkerk, Rotterdam.)

weight of the apparatus is too large, subdivision into parts each weighing a few hundred kg. is necessary (Figs. 7 and 8). Suitable tube stands can reduce the positioning time to a marked extent; in many cases provisional stands can be made on the site with economy. Long cables (e.g. 10–20 metres) are needed in order that the total time for transporting the generator may be small compared with the total time for positioning the tube. An oxtail tube as such is seldom needed, and it is better to use the single-cable tube of Fig. 9 as it is more robust. This tube also allows the rays to be directed along the plane of a girder to find lack-of-penetration faults.

Mobile apparatus (Fig. 10) is often used on this work. The apparatus is transported in a motor-car which houses also the dark-room and accessories. At present about 16 such installations are in operation on the Continent: 1 or 2 in Belgium, 1 in the Netherlands, and about 13 in Germany. The staff per car is composed of two or three men skilled in photographic technique; sometimes some unskilled men are employed in addition. The results are interpreted by experts, who are sometimes those of a central body in order to ensure unity in judgment.

The influence of X-ray inspection on the quality of welds on bridges in Germany is shown in Fig. 11. After a rise at the time when the more sensitive X-ray inspection was adopted, the number of repair welds decreased to about 1·5 %, the present figure.

Iron castings are usually inspected photographically, screening being only used for some thin objects. The wire sensitivity is perhaps not always needed but it is used in most cases. Whether portability is essential or not, depends on the kind of work, but easy adaptability of the tube, and high voltages, are nearly always necessary. The oxtail tube of Fig. 5 extends the use of X-rays for castings because it allows the X-ray source to be taken to every hole and corner.

High voltages are needed not only for large thicknesses, but also because large differences of thickness occur. These are compensated by filters of heavy metals like lead, allowing the piece to be examined in one exposure instead of several, one for each thickness. To oppose the increased absorption, higher voltages may be used, as the filters improve the sensitivity by absorbing the scattered radiation more than the primary pencil. The reason is firstly that the wavelength of the scattered radiation is slightly longer, owing to the Compton effect, and secondly that most of the scattered radiation passes obliquely through the filters whereas the primary radiation passes perpendicularly.

For use at voltages in excess of 300 kV the apparatus is not yet made in portable form. Fig. 12 shows a

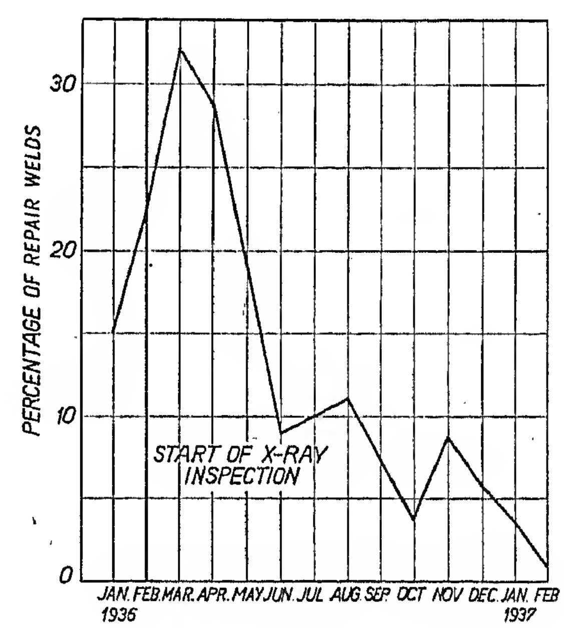



**Fig. 11.**—The influence of X-ray inspection on the quality of the welds on German bridges. (Reproduced by the courtesy of Dr. Berthold, Berlin.)

shock-proof and ray-proof apparatus for 400 kV with tube and generator enclosed in one housing. The tube can be moved up and down and rotated about its axis. Apparatus up to 1 000 kV is being used for medical purposes, even with tubes with earthed anode.* The penetrable thickness is limited even with very high voltages because the half-value layer increases less and less with the voltage, although the dose increases steadily.† Gamma-rays, having a still higher penetrating capacity,

* A. Bouwers: *Radiology*, 1938, vol. 31, p. 89.

† J. H. van der Tuuk: *Fortschritte auf dem Gebiete der Röntgenstrahlen Kongressheft*, 1938.

are used more for heavy castings than the very-high-voltage tube, because the latter has only recently become available and because the portability of radium is better than that of the high-voltage tube ever will be. The exposure times are, of course, much smaller with the X-ray tube.

Castings of light metals are usually screened. Voltages above 150 kV are rarely necessary. High currents and small filters are needed; good portability is as a rule only necessary when screening and photography are done with the same apparatus. The oxtail-tube has not yet been used for screening; the short-anode tube of Fig. 9 suffices. Its filter is 0·2 mm. of copper.

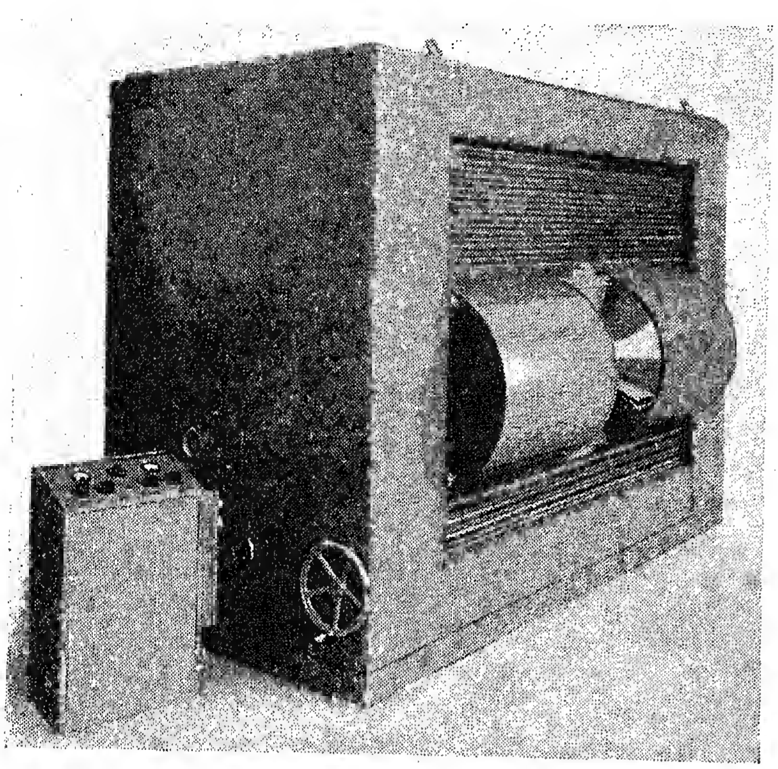


Fig. 12.—Fully-protected apparatus for 400 kV.

### THE USE OF RESULTS FOR THE ACCEPTANCE TEST

This use is, in general, simple when checking whether a part is present or in its right position or of correct size. But difficulties arise when the influence of flaws on mechanical strength has to be determined. One might expect the correlation between X-ray picture and strength to be only very loose, because, even if all details of a flaw were depicted, the stress distribution cannot be calculated by applied mechanics. Moreover, different materials under the same stress distribution behave differently; they can yield more or less or crack brittlely. It is not known sufficiently what stresses are dangerous, and when.* It follows first of all that correlation of X-ray picture and strength can only be expected if the experimental flaws are produced in exactly the same way and degree as in practice. In welding, for instance, this means that not only the same material and electrode should be used, but also the same seam, welding method, and cooling conditions. Even flaws of one kind should not be regarded as the same: they should first be divided into groups according to cause (if the same kind can be produced by different causes, interpretation is often possible by aid of other flaws), and then according to dimensions.

It might further be expected that the strictest correlation will exist with those flaws where the chance is least that sharp corners and edges will be produced. Faults developed in the liquid state, such as gas pores and slag-inclusions, would thus offer better possibilities than cracks and lack of penetration.

One of the first researches was carried out on welds by Lefring,* who showed that under his conditions (mild steel) the tensile strength perpendicular to the seam was approximately proportional to the surface with good penetration (i.e. the total surface diminished by the surface with lack of penetration). This might mean that stress concentrations played no important role, but this will by no means always be true with such faults. Berthold† found with fatigue tests that uniformly-dispersed pores in welds are far less dangerous than rows of pores. Wallmann,‡ who confirmed this, was the first to produce Wöhler fatigue pictures for some kinds of faults, demonstrating that for the faults in hand (small and large pores, lack of penetration) the reproducibility was sufficient. This makes it plausible that when the same faults under the same conditions occur in actual practice their influence in a test-piece can be estimated with reasonable certainty. Wallmann§ and Tofaute|| found that pores in welds had far more influence on the elongation than on the tensile strength. This might depend on the cause of porosity; gas content may in certain cases be more efficient in reducing the elongation than the geometrical configuration of pores. Tofaute came to the conclusion that often the influence of flaws is most evident on elongation and impact value (fatigue tests were not carried out), and that in his case (mild steel, coated electrodes) the most dangerous flaws were due to lack of penetration and non-welded roots of the seam. One might include cracks with these, yet no systematic investigation seems to have been done on them, presumably because they are very difficult to find with X-rays. Recently Müller¶ showed some examples of faulty welds and their influence on the tensile strength, and Möller** investigated the correlation between fatigue resistance and some kinds of inclusions on a somewhat larger scale than Wallmann. He found that the reproducibility of his faults (which all seem to have been made in more or less liquid metal) was also sufficient to enable the Wöhler curves to be measured.

In the case of welds it seems that, after a series of experiments under the particular conditions prevailing, it will be possible to estimate the influence of flaws caused when the metal is more or less liquid, such as gas pores and slag-inclusions, within 3 or 4 kg./mm.$^2$ when the test-piece is made from the weld at the position of the flaw. Acceptance and rejection are then based

* R. A. STEPHEN: *Quarterly Transactions of the Institute of Welding*, April, 1938.

* N. LEFRING: *Forschungsarbeiten auf dem Gebiete des Ingenieurwesens*, 1930, No. 332.

† R. BERTHOLD: *Zeitschrift des Vereins deutscher Ingenieure*, 1934, vol. 78, p. 173.

‡ K. WALLMANN: *Archiv für das Eisenhüttenwesen*, 1934–35, vol. 8, p. 243.

§ *Loc. cit.*

|| W. TOFAUTE: *Archiv für das Eisenhüttenwesen*, 1934–35, vol. 8, p. 303.

¶ E. A. W. MÜLLER: *Archiv für das Eisenhüttenwesen*, 1938–39, vol. 12, p. 25.

** H. MÖLLER: *Berg- und Hüttenmännische Monatshefte*, 1938, vol. 86, p. 148.

rather on rational data, although no investigations seem to have been carried out to estimate the influence of a flaw on larger welds such as complete boilers. As to cracks, lack of penetration, and similar faults with high notch effects, the estimation of influence remains very uncertain and the utmost caution is necessary.

On flaws in castings far less work has been done, presumably because the variety of flaws is still larger and because the properties even of sound castings themselves often vary largely. An instance is given by Frommer, Kuntze, and Sachs,* who investigated the strength of porous and homogeneous aluminium die castings. They found that the influence of common porosity (about 10 %) was smaller than the normal variation of the properties (about 20 %), due to differences of microstructure. This proves that in this case the lower sensitivity of fluoroscopy is sufficient for the radiological inspection, as only larger flaws have to be sought.

* L. Frommer, W. Kuntze, and G. Sachs: *Zeitschrift des Vereins deutscher Ingenieure*, 1929, vol. 73, p. 1609.

[The discussion on this paper will be found on page 580.]

# ACOUSTIC AND GENERAL METHODS OF NON-DESTRUCTIVE TESTING

By S. F. DOREY, D.Sc.*

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## CONTENTS



## (1) INTRODUCTION

A non-destructive test may be defined as a means of proving some particular quality of an article without impairing its adequacy for the service for which it is intended to be used. The definition might be extended to include tests on test samples which may subsequently be subjected to further tests either of a destructive or non-destructive character; for example, the carrying out of a Brinell hardness test on a tensile specimen prior to pulling the specimen might be mentioned.

Although the results of many non-destructive tests—some of which will be instanced in this paper—are capable of precise interpretation, in general the particular qualities which they are designed to prove can only be assessed by inference, whereas the destructive test gives a positive indication of the ultimate resistance of an article to the testing conditions imposed upon it.

* Lloyd's Register of Shipping.

## (2) ACOUSTIC METHODS

Perhaps the oldest acoustic method of testing is that of listening to the sound produced by giving an article a sharp blow. The sounding of railway-carriage wheels is a practice familiar to every traveller whether of a technical turn of mind or not. It is instinctive on the part of the engineer who doubts the soundness of an article to give it a tap and listen for the ring. The production of a pure note corresponding to the natural frequency of vibration of the article may be taken as indicating that the article is sound and free from serious defects. The converse may not always be true, and whilst the absence of any note at all must raise doubts regarding the soundness of the article, it is necessary to take into account various factors such as the degree of restraint imposed on the article under test, its method of support, attachments, etc., any of which may have a damping effect on the vibrations produced in the article by a blow, or give rise to secondary vibrations which cause the " note " to be " reedy " or " harsh." Again, in certain circumstances the natural frequency of vibration may be of such a high order that the note produced may be inaudible to the human ear.

Obviously, therefore, the sounding method of test, whilst extensively used in practice, cannot be regarded as infallible, but used with discretion it can be extremely helpful in indicating the possibility of defects being present.

Referring again to the hammer testing of the wheels of rolling stock, it is understood that railway engineers do not attach much value to the test. Wheel-tapping is a survival of the days when tyres were not reliable, and it provided an effective method of revealing a defective tyre, but on certain trains it has been discontinued, particularly on sleeping-car trains, as it is a source of annoyance to passengers. The practice has, however, not been entirely discontinued, as it affords an audible indication that the examiners are passing along the train from end to end to carry out their examination of the axle-boxes and general running gear; also, in the remote contingency of a tyre failing, there would be a clear indication.

A refinement of the " sounding " method of test has in recent times been effected by the use of an ordinary medical stethoscope. It has been applied to some extent for the testing of structural welds. A rubber cap is fitted over the searching end of the stethoscope, which is then placed against the welded plate whilst the weld under examination is tapped with a hammer. A high-pitched reedy sound occurring in the primary period of sound caused by the hammer blow is taken to indicate

the presence of defects in the weld. The method has been investigated in this country at the National Physical Laboratory* without any special success, and it was concluded that stethoscopic examination could not be recommended as a useful practical method of non-destructive testing of welded joints in structures.

Magnetic acoustic methods of testing welds have been developed, but in the main have met with little success outside the laboratories. The methods involve magnetizing the article under test so that a magnetic flux passes through the weld. Defects in the weld cause a disturbance in the flux lines, distorting the field in the vicinity of the defect. The " tester " comprises a searching device connected up, through an amplifier, to earphones. The searching device consists of an electromagnetic vibrator which produces a characteristic " hum." The intensity and pitch of the " hum " undergo a change which can be detected in the earphones whenever the searching device approaches the distorted magnetic flux in a defective weld.†

One of the most interesting and valuable developments in non-destructive testing has been in the design of objective noise-meters. In this country most of the development work has been carried out at the National Physical Laboratory. The apparatus has been described in a paper by A. H. Davis,‡ and is an instrument of the microphone-amplifier-meter type which has been adjusted for measuring the equivalent loudness of noise.

The instrument has been of special use in the motor vehicle trade and in the construction of high-speed railway trains, in which the question of noise reduction has become important in recent years. A useful application has been that of testing gears by what is known as " noise analysis." In this the objective noise-meter is used for locating the pitch (i.e. frequency) of the noise and leads to the detection of the source when the frequency of meshing of the gear wheels is known. The instrument has also been used for testing squirrel-cage motors by noise analysis, it being suggested that faults can be detected by these methods.

Acoustic tests for timber have been devised by the National Physical Laboratory, where, at the request of the Forest Products Research Laboratory, experiments were carried out to explore the possibilities of applying microphone and amplifier technique to the detection of destructive larvae in timber, by listening to the faint sounds made by such larvae when eating or moving about in the timber.§ The apparatus devised at the National Physical Laboratory necessitated the placing of samples of the timber in a sound-proof container for the purpose of the test, but it is understood that apparatus has also been produced in Germany which can be applied to the timber of an actual building.

In these days architects and building contractors pay great attention to the acoustic properties of the materials used for walls, ceilings, and floors. The subject is of special importance in the case of hotels, flats, public halls, and theatres, and in accommodation spaces in luxury passenger ships. The testing of the sound-insulating properties of materials can truly be classed as non-destructive in character. The tests comprise the measurement of sound-absorption coefficients for different materials by the reverberation method. The tests are carried out in a reverberation chamber of high acoustic isolation, one wall of the chamber being arranged to accommodate the specimen panel which is to be tested. The sound-absorption coefficients are calculated from instrumental measurements of the period of reverberation of the chamber, the measurements being taken under two conditions, first with the test panel exposed inside the chamber and second with the test panel adequately covered, generally by means of steel doors. The coefficients thus derived relate to the fractions of the incident sound energy absorbed by the specimen. Most of this work has been carried out at the National Physical Laboratory.*

* See Reference (1). † *Ibid.*, (2). ‡ *Ibid.*, (3). § *Ibid.*, (4).

### (3) OPTICAL METHODS

It is proposed to include under this heading those methods of testing which embrace the sciences of optics and colorimetry.

In the study of atmospheric corrosion and tarnishing of metals and alloys it has been found necessary to develop methods of optical examination of polished surfaces which will facilitate the assessment of the degree of polish. For this purpose apparatus has been devised for the quantitative determination of specular and diffuse reflectivity.† The specular reflection factor is measured as the ratio of the observed brightness of an illuminated white object after reflection at a prism, the reflection factor of which is known. The diffuse reflection is measured as the ratio of the brightness of the surface under test to that of a matt white surface under standard conditions of illumination and direction of view. For laboratory work, of course, it is necessary to use samples for testing purposes, but the same principle is involved in the design of portable instruments, such as glossmeters, which can be applied to the actual objects which it is desired to test.

Another method used in industry for assessing the degree of polish or gloss is to compare the perfection of images of suitable patterns reflected in the surface under test. This method is simple, cheap, and readily applicable, but depends directly on normal visual appreciation of gloss.

These methods are in the main used for the testing of metallic material in which surface finish is important, for the measuring of lustre in textile materials,‡ for the control of surface appearance of decorative paints, varnishes, lacquers, etc., and the comparison and calibration of light sources, such as incandescent gas mantles and electric lamps.

An optical method of checking the chemical analysis of metals is provided by the spectroscope. The test is not entirely non-destructive in character as it requires the striking of an arc between an electrode and the material under test. This causes a small burn or scar to be left on the specimen. The principle of the method is based on the fact that each element contained in the material emits characteristic rays of definite wavelength, the quantity of rays produced being directly dependent upon the amount of the element contained in the material. Analysis of the spectrum is carried out by means of a quartz prism in conjunction with a

* See References (5) and (6). † *Ibid.*, (7). ‡ *Ibid.*, (8).

collimating lens which renders the rays of light parallel before they reach the prism, and readings may be made by direct visual observation of reflections on a suitably arranged graphical screen, or by means of a microphotometer with which precise determinations, which are independent of the human element, can be made. The former method relies on the visual observation of the person making the test, in order to judge the intensity of the rays and so determine the quantity of the elements contained in the specimen. It is understood that spectrographic analysis is capable of determining the presence of elements in quantity greater than 0·0001 per cent.

An interesting and simplified adaptation of the spectroscope is to be found in an instrument called a "Spekker Steeloscope" which has been developed for works use as a means of rapidly checking large numbers of alloy steel samples, thus reducing the amount of quantitative analyses to be carried out by chemical methods. As in the spectroscope, a direct-current arc is struck between the steel to be examined and another electrode, which may be commercially pure iron or mild steel free from the elements it is desired to detect. The light from the arc, passing through a fine vertical slit, is directed upon prisms, which split the rays into their constituent wavelengths and project them towards a movable screen and eyepiece. The lines which appear are coloured according to their position in the spectrum, and each represents the image of the slit produced by its own particular wavelength. The manufacturers of the "Steeloscope" have provided charts which enable an operator after some experience to detect quickly the presence of various important alloying elements. The elements which are most readily detected are nickel, chromium, molybdenum, manganese, titanium, tungsten, cobalt, copper, and vanadium.

A simple shop method of checking the quality of steel is by means of the "spark test." The metal is held in contact with a grinding wheel, and the shape, colour, and distribution, of the spark bundle are observed. Each grade of steel, depending upon its carbon content and the presence of alloying elements, produces a characteristic spark bundle, the recognition of which requires considerable experience. The test is purely qualitative and then only within wide limits.

Analysis of stress distribution in ferrous material is entirely a laboratory process, but it is considered relevant to make a brief reference to it as a non-destructive test on the specimens used. The material used for the specimens is transparent and is usually glass, celluloid, or bakelite. These materials, in addition to being very similar to ferrous metal in elastic behaviour, possess valuable optical properties. The form of the specimen is made to resemble the form of the article or structural member in which it is desired to analyse the stress distributions. The test is based on the fact that glass when stressed behaves like a natural crystal having unequal optical axes, and thus exerts a directive action on plane-polarized light. The beam of polarized light is obtained from an apparatus which consists of a projection lamp and a suitable prism or reflecting device so arranged as to have a selective action on the rays of ordinary light from the lamp, only allowing the components parallel to one plane to pass. A ray is therefore obtained in which the light vibrations are limited to one plane, and this ray is termed "plane polarized."

If a stressed specimen having optical properties is placed in the path of a beam of plane-polarized light, the plane vibrations are split into two components having different properties in regard to velocity and direction. By passing them through another prism similar to the first, the components of each ray parallel to the principal plane of the prism will be transmitted. These emerge as two separate unidirectional rays in the same plane, and their interference with each other produces colour effects which consist of bright and dark bands if homogeneous light is used, or brilliant chromatic colours if white light is employed. These colours or bands when interpreted in accordance with a particular law are measures of the stress in the specimen.*

The above principles of photo-elastic analysis form the basis of the design of instruments used in the glass industry for showing at a glance the presence of strain in commercial glass articles. Such instruments are generally called "glass wall strain viewers" and comprise a simple and portable piece of apparatus which can be used in the factory test-house.

An instrument has been developed for measuring the thickness of glass and is widely used in examination of hand-made technical glassware, which is always liable to contain variations in thickness. The principle on which the instrument is based is to measure the difference between the optical paths of images reflected from the front and back surfaces of the glass when illuminated by parallel light. At the end of the instrument there is a scale on which the two magnified images are projected. The scale is so calibrated that the difference between the readings opposite the two images gives the thickness of the glass. In practice the instrument is traversed over the surface of the article, and variations in thickness are readily located by the two images either approaching each other or separating beyond predetermined limits.

The measurement of the transmission properties of electric light globes is important, especially in the case of opal lighting units. For the purpose of the test the globe is placed in an internally whitened box, known as the integrator, which is much larger than the globe itself. If the walls of the integrator are uniformly white the brightness will be directly proportional to the amount of light emitted from the globe, and this is measured by a photometer which can be calibrated either in terms of the total light emitted or in terms of the proportion absorbed by the glass itself. It is understood that this test is applied to a high percentage of the globes made for the better-quality lighting units, and a British Standard Specification is adhered to.

The microscope in one form or another is now in general use in factory test-houses, and whilst this may more properly be described as a non-destructive method of examination, rather than a non-destructive test, it is thought well to mention the matter in this paper.

In various branches of industry, such as glassware manufacture, potteries, textiles, paints and varnishes, etc., paper-making, breweries, dyes, and many others,

* See References (9) and (9*a*).

also in many spheres in which it is necessary to match colours or to deal with colour problems, it is now possible to apply methods of test which are the result of much laboratory work directed towards the establishment of a scientific system of colour measurement.

Apparatus is now available which enables colour measurements to be made in such a way that they can be expressed numerically in terms such as wavelength distribution and energy, and colours can be reproduced from the figures obtained.

There are two types of colorimeters:—(1) Spectrophotometric in which, by use of a suitable spectrometer, the energy distribution of light reflected from the sample over the visible spectrum is analysed. (2) Trichromatic, in which the colour of the sample is expressed in terms of

(a) relative amounts of three coloured standard lights, accurately calibrated in terms of wavelength, required to effect a match,

(b) the intensity or brightness of the light reflected.

The spectrophotometric or objective type of colorimeter replaces visual observation by photoelectric methods and is therefore independent of the human conception of colour tints and shades, but the trichromatic or subjective type renders colour form more easily interpreted in terms of visual sensation; it is rapid in use and capable of a high order of accuracy and not so costly as for accurate spectrophotometric measurement. The latter has found some favour in the United States of America, but trichromatic methods are almost exclusively used in Great Britain.*

Other tests which might be mentioned in this section are those used in the textile industry for measuring whiteness of fabrics by visual comparison with arbitrary standards prepared from mixed coloured powders, the detection of oils and fats in textile materials by fluorescence in ultra-violet light, and the detection of faults by means of micro-stereoscopic examination.

The use of ultra-violet light in the testing of textile material is of special interest, and suitable portable lamps have been designed for this purpose.† The principal applications of this non-destructive test are in the detection of oils, fats, and waxes, and in the examination of dyed materials. The method makes use of the fact that certain mineral or paraffin oils fluoresce with a brilliant reddish-blue colour in ultra-violet light, and other oils vary in the ultra-violet fluorescence colours which they yield, from blue to yellow. Dyestuffs when dyed on textile materials show fluorescence colours in varying degree when examined under the lamp.

In the paint trade, opacity may be measured by applying the paint to a surface of known area in sufficient quantity to obliterate a standard contrast of black and white areas on the surface, though a more accurate determination of opacity is obtained by measuring photometrically the amount of light transmitted by the film, and for this purpose an instrument known as the "Transmeter" has been designed at the Paint Research Station.‡

## (4) GENERAL METHODS

A hydraulic test in some form or other is possibly the first non-destructive test which comes to mind in connection with engineering constructions. It is widely used in industry, for proof-testing pipes, hollow forgings and castings, pressure vessels, and all manner of fittings and containers; it may be applied as a pressure test or as a leakage test with no pressure, or as an external pressure test such as may be given to watertight structures (e.g. ships' bulkheads) by the impingement of a jet of water at high velocity from the nozzle of a water hose.

The hydraulic internal-pressure test serves a double purpose in that it exposes leaky joints and may therefore, in the case of such vessels as riveted boilers, be taken as a test of workmanship. Further, if the pressure applied is higher than the designed working pressure of the vessel, the test may be taken as indicating that the vessel is strong enough to withstand the proposed working pressure. It is, however, necessary to bear in mind that in the majority of cases this test does not simulate working conditions, and it cannot therefore be taken as a proof that the vessel is entirely suitable for the service intended.

Another test for leakage is the air-immersion test in which the article under test is filled with air at a suitable pressure, generally about one-half of the hydraulic test pressure, and then immersed in water. This is a sensitive test for leakage at joints or porosity in the material and is capable of revealing defects which the ordinary hydraulic test may fail to disclose. For this reason the air-immersion test is often carried out in addition to the hydraulic test.

A variation of this test is used in the refrigeration industry. The vessel is filled with air containing a small proportion of ammonia, and leakage is detected by means of a moistened litmus paper or a burning sulphur candle.

A leakage test which is often applied to tanks and fluid-tight containers is to fill the vessel with a light oil such as paraffin to a certain pressure head, after painting the joints and seams with whitewash. Any slight leakage of oil is at once revealed as a stain on the whitewash.

Mention might also be made of a general method applied to aluminium and aluminium alloys which consists of the indirect use of anodic oxidation as a means of detecting cracks and flaws in forgings and castings. Cracks and other flaws which are invisible on the surface of untreated parts appear clearly in the form of streaks, spots, and other blemishes in the oxide film, and are thus readily detected.

The ordinary mechanical tests usually applied to ferrous and non-ferrous materials are of a destructive character so far as the specimen is concerned, with the exception of the hardness test,* and those methods of visual examination such as micro- and macro-etching and sulphur printing.

The hardness test becomes important in the case of metals which are required to have special wear-resisting properties, but it is also applied as a rapid check on tensile strength and finds considerable use in laboratories in the investigation of problems such as those relating to the effect of temperature and the effect of mechanical work done on the material.

* See References (10) and (11). † *Ibid.*, (12). ‡ *Ibid.*, (13).

* See Reference (14).

There are several methods of making hardness tests, the most common being those of the Brinell and Vickers diamond methods. What might be called a dynamic indentation method has been developed in America. A diamond-pointed tool is dropped from a certain height and makes an instantaneous indentation at impact with the specimen. The apparatus is called the Ballantine Hardness Tester and the hardness number is obtained by the correlation between the absorbed energy and the dimensions of the indentation.

Hardness-testing methods also include the Shore scleroscope in which a hardness number is obtained by measuring the height of rebound of a small diamond-pointed steel tool dropped on the specimen from a known height, and various forms of " scratch " test in which the width or depth of a scratch is measured microscopically, the scratch being made by a diamond-pointed needle under standard conditions of loading.

Whilst the above hardness tests may be described as non-destructive, it should be noted that in each case the specimen receives a mark or indentation in the surface. From this point of view the least " destructive " form of hardness test is that of the pendulum hardness tester which makes an almost imperceptible indentation and can therefore be used on very thin material and on specimens in which it is desired to cause the least damage to the surface. Briefly, the apparatus consists of a pendulum mounted on a steel ball or diamond point which is made to rest on the specimen. The period of oscillation of the pendulum varies with the resistance offered by the surface of the specimen. The rate of oscillation is timed with a stop-watch and is taken as the measure of the hardness.

In the category of non-destructive testing may be included all forms of proof-testing applied to materials, machines, structural components, and finished structures. It is common practice in engineering to apply some arbitrary load or method of loading to a finished job or machine or structural part in order to " prove " its adequacy for the service intended, by demonstrating a suitable margin of strength. In this connection mention might be made of the proof-testing of chains, ropes, and lifting appliances, bridges and building structures, overload tests on electrical machines and prime movers, and certain forms of durability tests such as those applied to lubricants, paints and varnishes, etc.

Another test which, though destructive in character, only destroys a very small part of the structure, is a method which is employed to test the soundness of welds and is also useful in checking periodically the quality of workmanship. It consists of the use of a Schmückler milling machine which, by means of a special tool, mills out a small portion of the weld. Immediately after milling visual observation is made for defects such as blow-holes, pits, cracks, etc. To examine the penetration of deposited metal into the parent metal the milled surface is treated with a suitable reagent (cupric chloride, dilute nitric acid, or iodo-iodide). For ordinary mild-steel welds the best reagent appears to be 20 % dilute nitric acid; after attack by this reagent the deposited material is dark grey, the parent metal remaining white.

In glass manufacture methods of " thermal shocking " are commonly used for testing thermal endurance. The glassware is subjected for a certain period to the normal heat conditions which it will encounter in service, and is then plunged into water at a specified temperature. The glass should withstand this shock test without fracture. Such a test is described in B.S.S. 324—1934.

Certain types of glass globes, such as flameproof well glass used in mines, are subject to internal pressure in service, and are tested by internal water pressure of 100 to 150 lb. per sq. in.

In the space at the author's disposal it is impossible to do more than mention these tests, many of which have in themselves formed the subject of considerable discourse in technical literature. No attempt can be made here to exhaust the subject of general methods of non-destructive testing, and in the following concluding paragraphs the author will indicate as briefly as possible a number of tests which are in general use in various branches of industry.

Non-destructive testing is much less used for textile material than in the case of materials of construction, largely owing to the fact that it is generally made into relatively small and inexpensive units and the destruction of a few of these units by testing methods is generally practicable. Much testing of fabrics as regards harshness, pliability, elasticity, and resistance to crushing, is done by hand and is non-destructive. The judgment of experts in the handling of raw and manufactured textile material, in many cases determines its value. Raw cotton and fleece wool, for example, are seldom bought on the basis of laboratory tests, etc.

In the timber trade, for certain special purposes, e.g. testing telegraph cross-arms, the modulus of elasticity is determined by loading with a non-destructive load. Identification of timber species can generally be carried out by micro- and macro-scopic examination without destruction of the sample, and measurement of moisture content can be done by the use of electric meters which can be applied to the wood without causing destruction. These electrical methods depend on the indirect measurement of the electrical resistance of the wood, which varies with its moisture content.

The specific gravity test is used for the purpose of checking the density and homogeneity of solid materials in a large variety of industries. It is a simple and well-known test of a non-destructive character.

In rubber manufacture the following properties can be determined without destroying the sample:—Resilience, hardness, thermal conductivity, coefficient of friction, and permeability to gases. Rubber tyres can be tested for their load-deflection properties under different inflation pressures, and for skidding tendencies; belting for stiffness and adhesion to pulleys, and rubber balls for weight, size, compressibility, concentricity, and bounce.

Certain special methods of non-destructive testing are employed in the paper-making industry. Stretch is measured by means of a special recording fitment attached to the tensile tester. Air permeability is measured by a Densometer apparatus,* smoothness by means of a smoothness tester,† and whiteness and

* See Reference (15).

† *Ibid.*, (16).

opacity can be determined by a variety of instruments.*

An interesting and ingenious method for determining the directions of the principal stresses in, say, a structural member under load, is to coat the member with a thin layer of lacquer or shellac having a very low elongation on fracture and of very great adherence. When the member is loaded, fine cracks are developed in the coating perpendicular to the direction of the principal stresses. Tests made by this method have been applied to such items as casings, crankshafts, connecting rods, pistons, etc.†

Further general methods of non-destructive testing, the details of which cannot be included in this résumé, include tests for porosity in bricks, viscosity tests for oil and other liquids, tests for consistency of cement, lime, gypsum, etc., sieve tests for fineness of powdered material, flour, etc., and tests of boiler feed-water for acidity, alkalinity, and density.

It will be appreciated that the whole field has not been covered in this brief survey, but it is thought that sufficient has been said to indicate the varied nature of non-destructive methods of testing at present in use in industry.

The author has received much interesting and useful information from a number of sources and his inquiries have met with generous response from those engaged in testing of materials and research work in a variety of industries, many of whom are acknowledged authorities in their particular sphere of work. He wishes to place on record his appreciation and thanks for this assistance and regrets that limitations of space preclude a more detailed review of the comprehensive subject of non-destructive testing.

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[The discussion on this paper will be found on page 580.]

# MODULUS OF ELASTICITY AND DAMPING IN RELATION TO THE STATE OF THE MATERIAL

By F. FÖRSTER, Dr.Phil., and PROFESSOR W. KÖSTER, Dr.Phil.*

(*Paper received 22nd July, and read at a meeting arranged by the* JOINT COMMITTEE ON MATERIALS AND THEIR TESTING, *25th November,* 1938.)

## INTRODUCTION

Recently a description was published of a new apparatus for determining the modulus of elasticity and the damping capacity. Various investigations have shown that these quantities constitute in many cases characteristic values for a material. The new method of measurement can be applied in two ways for the investigation of materials. It not only serves as a means of metallurgical research, but can also be used in various ways for the non-destructive testing of materials.

In measuring damping, the elimination of any supplementary influence due to plastic deformation during measurement is particularly important. Even minute stresses can greatly increase the damping. In methods hitherto used for the determination of damping, the test piece is exposed to deformation of greater or less intensity during measurement. Under these conditions the damping shows itself to be largely dependent on the stressing. The method in question, however, completely precludes any mechanical stressing of the test piece during measurement. The stresses recurring during the determination of the damping never exceed a value of 10 g. per mm.² and average less than 1 g. per mm.²

In this paper the definition of damping which has been adopted is $\delta = ln \frac{A_n}{A_{n+1}}$, where $A_n$ and $A_{n+1}$ are two consecutive amplitudes of a free vibration. It is therefore immaterial at which point of the vibrating body the amplitude is measured.

In the publications of Föppel, damping is defined as the energy loss $\Delta_u$ per unit of volume between two consecutive amplitudes. The relation between $\Delta_u$ and $\delta$ is given by $\Delta_u = \delta E\lambda^2$, where $E$ is the modulus of elasticity and $\lambda$ the amplitude. In Föppel's researches, the material was considerably stressed during the measurement of damping. In those researches which have been carried out on technical lines, the damping obtained depends on the load, whereas in the work dealt with in this paper, edge stresses of roughly 1 g. per mm.² were found. Thus, except in the case of ferromagnetic materials, the damping was found to be independent of the amplitude within the range investigated. The values of the damping given by the authors are constants depending on structural constitution.

Except for a few characteristic cases, the damping over the range investigated (30 to 5 000 $\mu\mu$) is found to be independent of the amplitude of the vibrations. The measurements of the damping can be regarded as physically well-defined characteristic values for the state of the material. Further, the fact of the existence of a damping with minimum stressing of the test specimen, and above all its independence of amplitude, obviously implies that there is no threshold below which a material can be stressed cyclically, so as to exhibit a state of true elasticity; in other words, elastic hysteresis is always involved.

## METHOD OF MEASUREMENT

If a metal bar supported by thin wires is struck, transverse vibrations are set up in the way shown in Fig. 1. With a test bar some 200 mm. in length and 10 mm. in

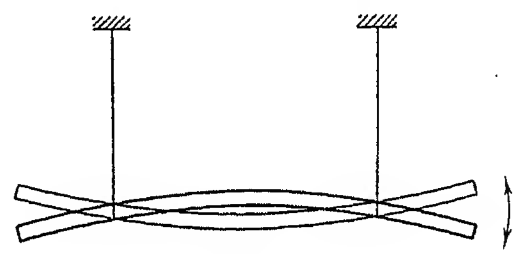

**Fig. 1**

diameter, the order of magnitude of the transverse natural frequency is 2 000 cycles per sec. Each end of the two wires used to suspend the specimen leads to a leaf spring F (Fig. 2) connected with an electrodynamic system. Mechanical vibrations are excited in the system S by an electrical buzzer, while the system E converts the mechanical vibration of the test bar into fluctuating currents, which are amplified.

The method of measurement is as follows: When the system S has been excited by the buzzer the test bar usually remains at rest, but if the exciting frequency approaches its natural frequency of vibration it will undergo vibrations which are stronger the closer the

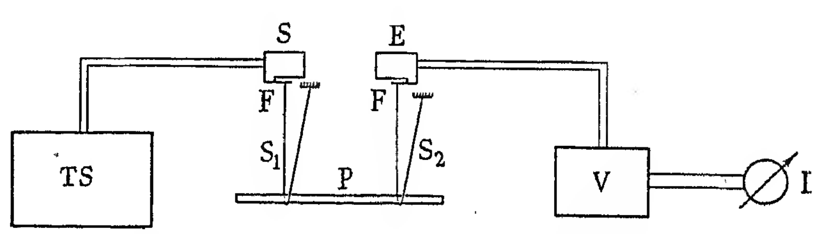


**Fig. 2.**—Arrangement for measuring damping.

ratio of its natural frequency of vibration to the exciting frequency approaches unity. One suspending wire conveys the vibrational energy of the exciting system to the test bar, while the other conveys the vibrations of the test bar to the receiving system, which feeds the amplifier with a current fluctuating in proportion to the amplitude of the vibrations, the value reached being read on the instrument I. The greatest effect is obtained when the exciting frequency is equal to the natural frequency of

* Kaiser-Wilhelm-Institut für Metallforschung.

the test piece. From the natural frequency determined in this way, the modulus of elasticity of the material (in kg. per mm$^2$) can be calculated, using the relation

$$E = 1 \cdot 6388 \times 10^{-8} \times \left(\frac{l^4}{d}\right) \times \frac{w}{l} f_n^2 \quad . \quad . \quad (1)$$

where $l$ is the length, $d$ the diameter, $w$ the weight, and $f_n$ the natural frequency of the test piece.

The dependence of the result obtained on the exciting frequency at about the natural frequency of the test piece is also shown by the resonance curve. Fig. 3 shows the striking difference between the resonance curves of copper and magnesium. Theory indicates that

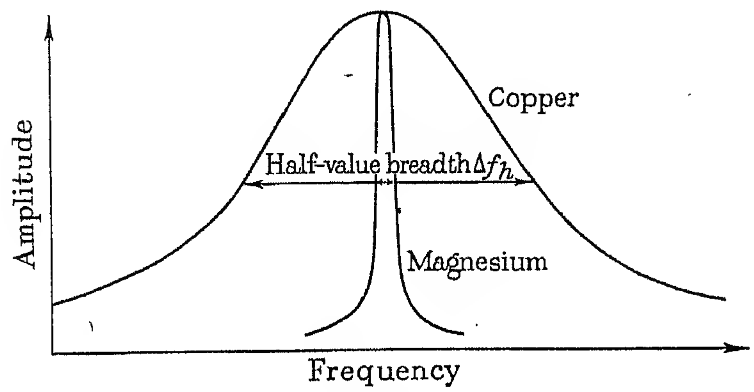


Fig. 3

the mechanical damping of resonance curves can be directly determined from their breadth. If $\Delta f_h$ represents the breadth (measured in vibrations per second) corresponding to half the maximum value, then the damping is given by the formula

$$\delta = 1 \cdot 814 \frac{\Delta f_h}{f_n} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The geometrical dimensions of the test bar do not enter into equation (2). As opposed to the modulus of elasticity, the damping can be determined for a system of any shape, provided it can vibrate. To measure the damping, three values on the resonance curve are required: the height of the maximum at the natural frequency of the test piece, and the two frequencies at which the amplitude has fallen to half the previous value.

If the test piece is made to vibrate and the excitation is suddenly stopped, the vibration dies away. The time taken for the vibration to die away can also be utilized to determine the damping. The time taken for an amplitude of value $A$ to fall to the value $A/2$—the so-called " half-value time " $t_H$—is related to the damping in accordance with the equation

$$\frac{0 \cdot 693}{t_H f_n} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Recently an apparatus has been developed which gives the product $t_H f_n$ independently, and enables the method of determining damping to be utilized for following rapid processes, i.e. for the determination of damping in tensile testing or during rapid variations of temperature. With this new apparatus, utilizing a thyratron coupling, the absolute value of the damping can be determined in 3 or 4 sec. with an accuracy of about 2 per cent.

A description follows of some of the results obtained with the sonic testing apparatus.

## PURE METALS

Table 1 gives the moduli of elasticity and the damping of a few pure metals at room temperature.

The values of the modulus of elasticity are in good agreement with the most reliable previous measurements. The high damping of nickel is noteworthy, the cause being attributable to the influence of the ferromagnetic state. Single crystals show a damping which is not much smaller than that of annealed polycrystalline material.

## DEPENDENCE ON TEMPERATURE

The dependence of the modulus of elasticity and the damping on temperature of numerous metals and alloys was determined. The method employed enabled measurements to be carried out simply from $-180°$ to about $+900°$ C., and some of the curves are given in Fig. 4. The steep rise in the damping of magnesium and aluminium is related to the appearance of new possibilities

**Table 1**

MODULUS OF ELASTICITY AND DAMPING OF SOME PURE METALS

| Metal | Modulus of elasticity, kg. per mm$^2$ | Damping | Remarks |
|---|---|---|---|
| Iron | 21·700 | $5 \cdot 6 \times 10^{-4}$ | Annealed 30 min. at 930° C., air-cooled |
| Nickel | 21·900 | $72 \cdot 1 \times 10^{-4}$ | Annealed 30 min. at 700° C. |
| Copper | 12·820 | $35 \cdot 5 \times 10^{-4}$ | Annealed 30 min. at 400° C. |
| Molybdenum | 59·100 | $5 \cdot 1 \times 10^{-4}$ | Sintered; annealed 1 hr. at 900° C. |
| Aluminium (99·99 % Al) | 7·230 | $0 \cdot 46 \times 10^{-4}$ | Annealed 30 min. at 550° C. |
| Magnesium (99·99 % Mg) | 4·530 | $2 \cdot 1 \times 10^{-4}$ | Annealed 30 min. at 550° C. |
| Zinc (99·99 % Zn) | 13·130 | $7 \cdot 7 \times 10^{-4}$ | Extruded; annealed 1 hr. at 200° C. |
| Cadmium | 6·250 | $11 \cdot 0 \times 10^{-4}$ | Cast |
| Bismuth | 3·480 | $17 \cdot 6 \times 10^{-4}$ | Cast |
| Lead | 1·450 | $45 \cdot 7 \times 10^{-4}$ | Cast |
| Tin | 4·560 | $54 \cdot 2 \times 10^{-4}$ | Cast |

of slip in the material. Obviously, the damping of an annealed metal is closely related to its plastic behaviour. The characteristic crystallographic behaviour of the metal, on which depends the change of shape under

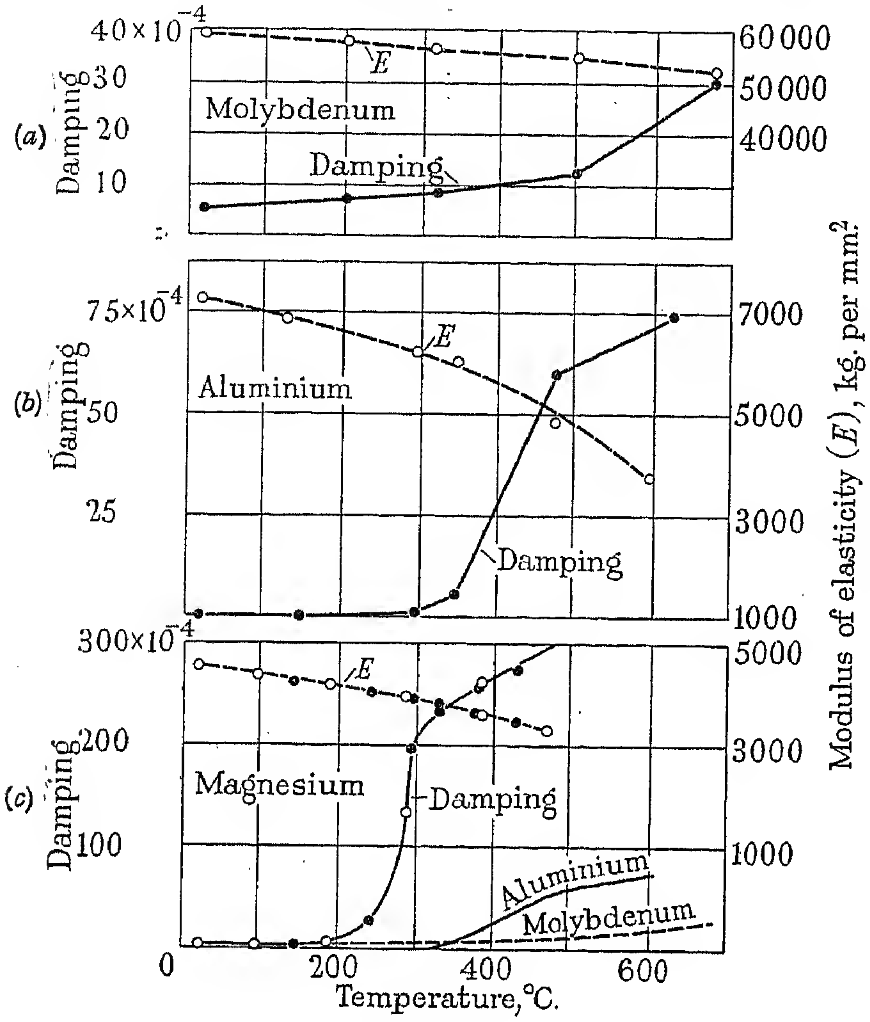


**Fig. 4**

extensive deformation, has, as many investigations have shown, a decisive influence with the slightest stressing (about 1 g. per mm.²) which can be regarded as elastic. The greater the capacity for deformation and the smaller the resistance to deformation, the greater the damping usually is.

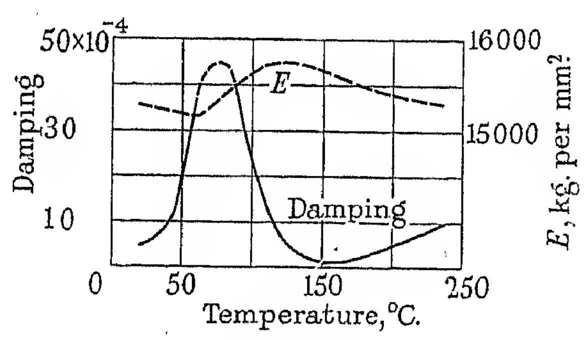


**Fig. 5**

## POLYMORPHOUS TRANSFORMATION

Examination of the dependence on temperature leads to suggestive conclusions if alloys undergo transformations in the solid state. Usually the damping increases considerably during the transformation. Fig. 5 shows the $\gamma\alpha$ transformation of an irreversible steel containing 22·4 per cent of nickel which had been heated to over the $Ac_3$ point. As would be expected, the modulus of elasticity increases with decreasing temperature. In the transformation range the fall is from 120° to 60° C., and when the change is complete the modulus again shows its expected behaviour. Before the change to the $\gamma$ state the damping decreases with decreasing temperature. During transformation the alloy is heavily damped

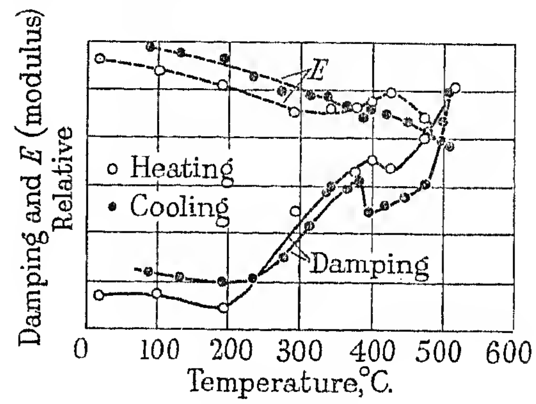


**Fig. 6**

and is particularly easy to deform. It is noteworthy that the damping begins to increase before there is a decrease in the modulus of elasticity. This behaviour, which

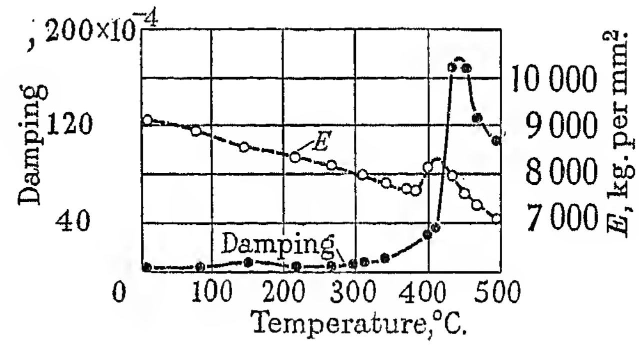


**Fig. 7**

points to a change in structure of the alloy preparatory to transformation, is shown in numerous other cases involving such transformation. Local variation in plasticity can also be detected during recrystallization

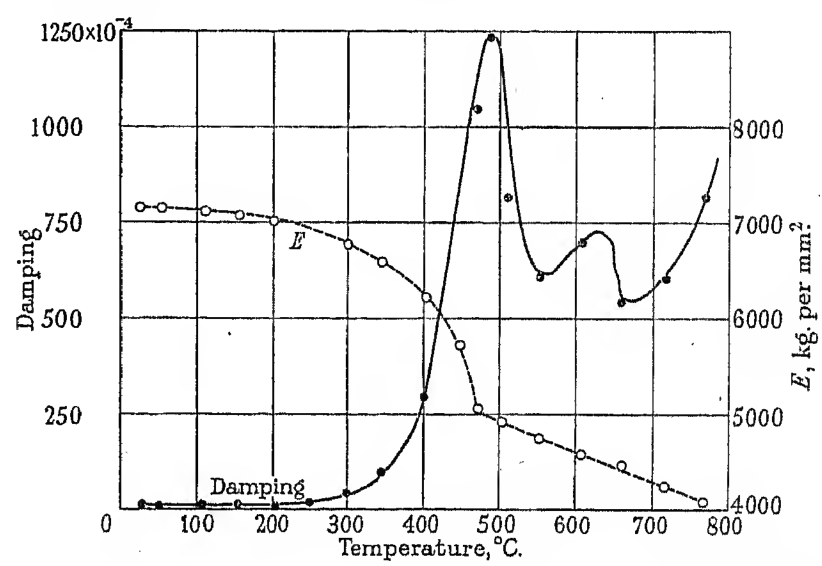


**Fig. 8.**—Dependence on temperature of the modulus of elasticity and the damping of $\beta$-brass.

by measuring the damping. These observations also show that conclusions regarding the plastic behaviour of materials can be drawn from measurements of the damping.

Fig. 6 shows the change of the modulus of elasticity and the damping of cobalt. During the transformation

of the hexagonal $\epsilon$-state into the cubic $\gamma$-state, both modulus of elasticity and damping show distinct instability. The temperature hysteresis during the change can be readily recognized. The decrease in damping in passing from room temperature to 200° C. can easily be correlated with the magnetic properties of cobalt. Further, the curve showing magnetization in relation to temperature has an inversion point at the point of minimum damping.

## ORDERED AND DISORDERED CONDITIONS

The transition from the ordered to the disordered condition is illustrated by the case of the gold-copper alloy AuCu (Fig. 7). The alloy, which had been annealed at 900° C. and slowly cooled, was examined while being heated. At the transition from the ordered to the disordered condition at about 400° C. the modulus of elasticity increases. The damping increases considerably, falls again, and then again increases at above 500° C. with the temperature. Here again, as with nickel steel, the two properties do not change in parallel. The damping is still irregular in the region of disordered solid solution.

The transition from the disordered to the ordered state of atomic structure in the gold-copper alloy AuCu is related to a change in lattice structure. In this case the modulus of elasticity changes abruptly at the transition temperature, though this does not occur when the condition of order is not associated with a change in lattice structure. With $\beta$-brass (Fig. 8), the modulus of elasticity is further raised, just as the electrical resistance is lowered with an increasing degree of order. In the range of disordered solid solution, the damping again shows the maximum which has so often been observed.

## MAGNETIC TRANSFORMATION

The ferromagnetic condition has a characteristic influence on both modulus of elasticity and damping. The effect of temperature on the modulus of elasticity and the damping of an iron-nickel alloy is illustrated in Fig. 9. In the ferromagnetic range the modulus of elasticity is smaller than when the alloy is in the paramagnetic state. When the Curie point is passed, the additional limit of the curve disappears. For this reason ferromagnetic materials often show remarkable behaviour in that with rising temperature the damping first decreases, until the spontaneous magnetization disappears above the Curie point, when it increases with the temperature, as would be expected. The magnetic transformation also makes itself clearly seen in the elastic-modulus/temperature curve. Noteworthy results have been obtained from the investigation of the relation of the modulus of elasticity and damping to temperature in the iron-nickel series of alloys.

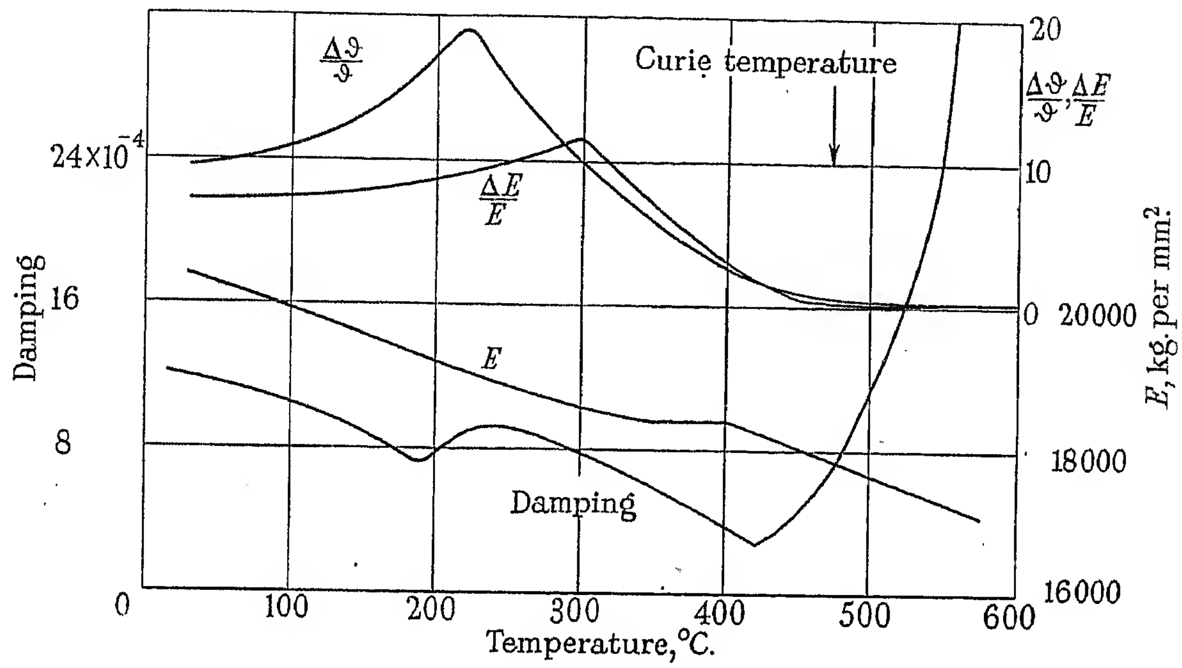


Fig. 9.—Dependence on temperature of the modulus of elasticity, the damping, and the amplitude, in an iron-nickel alloy containing 90 % nickel.

Ferromagnetic materials behave irregularly as regards

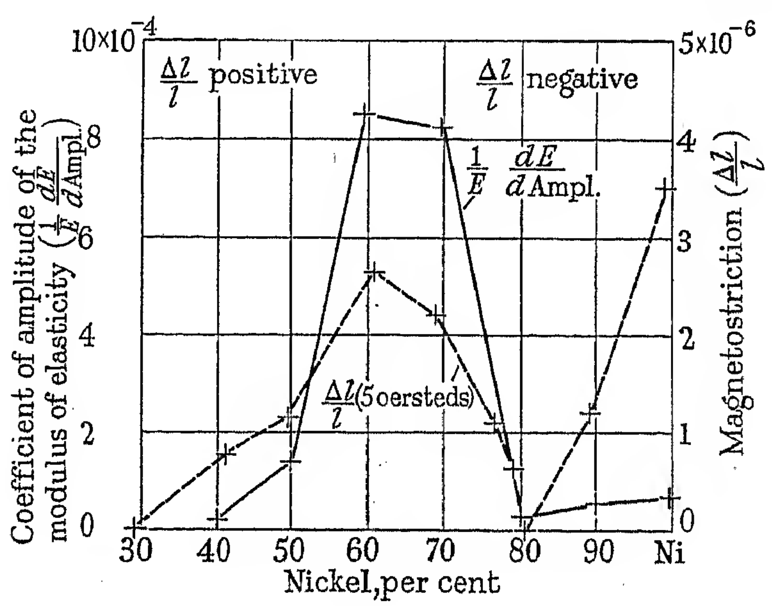


Fig. 10

the influence of the amplitude of mechanical vibrations excited in them. Whereas normal materials, as was mentioned previously, showed constant damping and modulus of elasticity over a range of amplitudes of

several powers of 10, this does not occur with ferromagnetic alloys. Fig. 10 shows the effect of amplitude on the values mentioned in the iron-nickel series. The close relation with magnetostriction is obvious. In every case the effect of amplitude disappears above the magnetic transformation.

## INFLUENCE OF ALLOY ADDITIONS

Further investigations were carried out on the modulus of elasticity and damping of various homogeneous and heterogeneous alloy systems. In general, these alloys show a lower damping capacity than their components. With the copper-zinc alloys, the damping may decrease to 1 per cent of that for copper, in accordance with the well-known observation that when a brass bar is struck it resonates longer than does a copper bar. In particular, stress-free $\alpha$-brass shows the smallest damping, namely $0 \cdot 2 \times 10^{-4}$, of all the materials investigated. This value can be measured easily and accurately by the method described in this paper. Further, in the iron-carbon alloys the damping decreases with increasing carbon content. Up to $0 \cdot 3$ per cent of carbon it falls to one-fifth of the original value.

Damping is closely affected by structural condition, while a change of structure is also reflected by the behaviour of the modulus of elasticity. In both series of alloys the resistance to deformation increases and the deformability decreases. The damping changes in accordance with the second-named quantity.

## GRAIN SIZE

A brass bar containing 72 per cent copper was annealed under a rising temperature for an hour, then tested immediately. The relation of the damping to grain size is illustrated by Fig. 11, which does not include the value of $10 \cdot 5$ for a grain size of $14 \times 10^6\ \mu^2$. The damping increases considerably with the grain size. As the

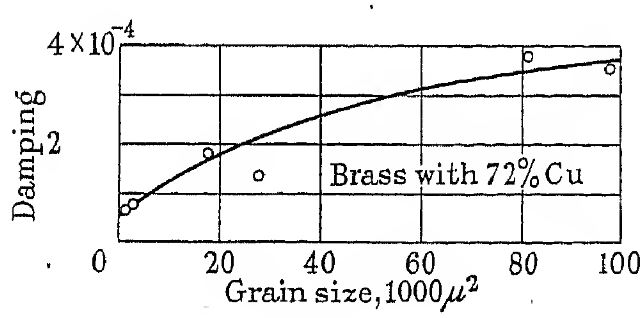


Fig. 11

resistance to deformation decreases with the grain size, so the damping increases with the deformability. In the investigations on iron, no influence of grain size was observed.

## PRECIPITATION HARDENING

The influence of precipitation hardening on the damping was investigated in the iron-copper system (Fig. 12). A bar air-cooled from 800° C. was annealed in half-hour stages under a rising temperature and air-cooled. On annealing the damping follows the hardness in its behaviour, the maximum value of the modulus of elasticity occurring at slightly over the temperature of maximum damping. In particular cases these phenomena can be freely explained from the usual behaviour of the physical constants under similar conditions.

## DEFORMATION AND RECRYSTALLIZATION

As the process described above produces extremely little stress in the material, it is particularly suitable for

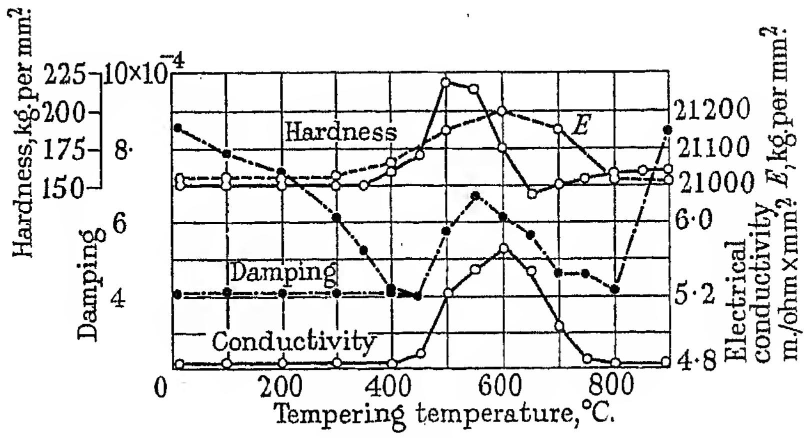


Fig. 12

ascertaining the modulus of elasticity of deformed metals. As is shown by Fig. 13, the modulus of elasticity of brass bar (72 per cent copper) drawn to half-size is about 12 per cent less than in the annealed condition. During annealing, it increases slowly up to 250° C. During recrystallization between 250° and 300° C. it changes abruptly to the value for the fine-grained annealed material. The hardness changes throughout in parallel with the modulus of elasticity. Particularly striking is the heavy decrease in damping in the first annealing range. This is readily attributable to the equalization

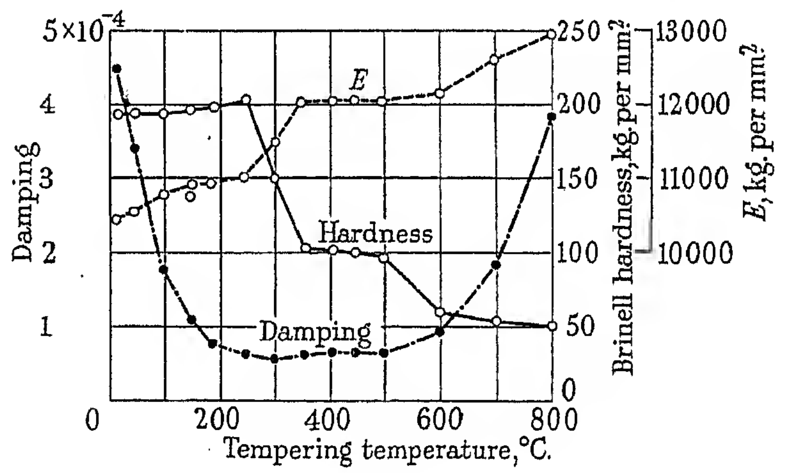


Fig. 13

of internal stresses, which have been exhaustively investigated in various materials. Recrystallization causes but a slight decrease in the damping.

## INTERNAL STRESSES

The damping characteristics enable alterations of the stress condition of a material to be followed in a particularly simple and sensitive way, without any fear of interference due to the method of test. Change in the internal stress in a single test bar can be followed in relation either to time or to temperature. In particular, the change in time of the internal stress in various deformed brass bars was studied exhaustively. After drawing, the damping approaches a constant value

according to an exponential function which decreases with time, this value being reached at room temperature after about 100 hours. This final value increases with the degree of deformation, and at higher temperatures it is reached in much shorter time. Fig. 14 compares stresses

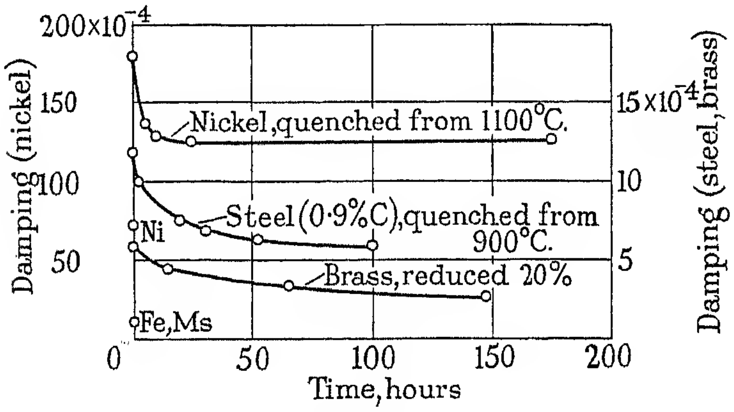


Fig. 14

due to heating, hardness, and mechanical working, the specimen being maintained at a temperature of 20° C.

## LOCAL DEFECTS

A special application of the measurement of damping concerns the detection of local defects. Faults of any kind in a material combine to raise the damping, so that cavities, cracks, pipes, pores, or damage caused during manufacture, are easily detected. For example, with ingots for forging, weighing some 100 kg., the damping increases by over 500 per cent if internal cracks are present. Examination during the finishing is rendered much easier by the self-indicating apparatus for measuring damping, the material whose damping is to be investigated being merely struck. In cylindrical test-pieces, the location of a crack can be detected. Fig. 15 shows the directional effect of damping in a material free from defects and stressing compared with a stressed material with internal cracks. The unstressed material shows the same value for the damping in all directions, whereas the stressed or defective material distinctly shows anisotropic damping.

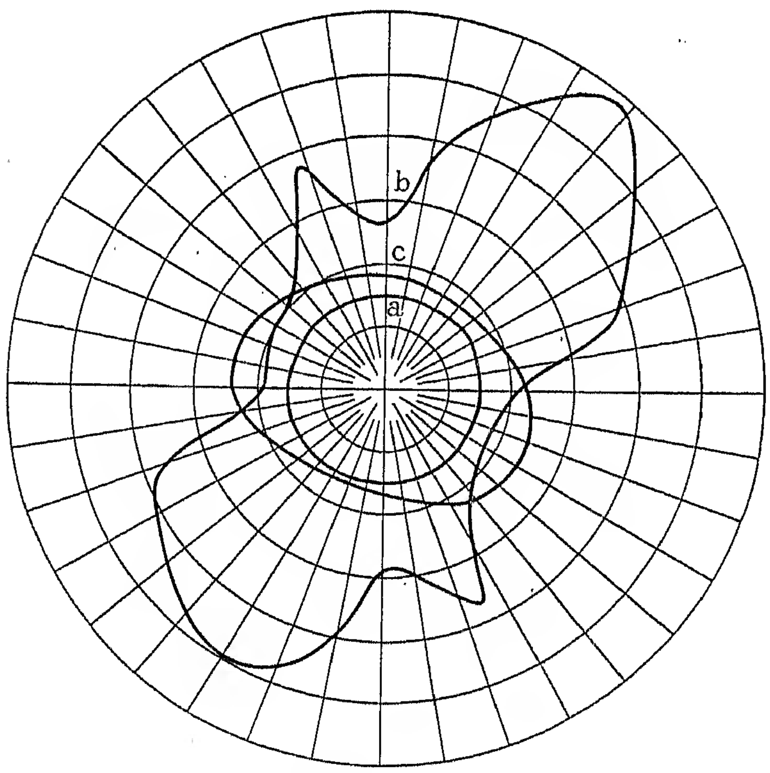


Fig. 15

Under certain conditions, the origin of defects can be traced by measuring the damping. If a steel is quenched at too high a temperature for practical use, the damping increases considerably with time after quenching (Fig. 16), the rise being due to the presence of fine hardening cracks. It is not easy to see these cracks in the structure and it is difficult to determine the moment when they are formed. By observing the variation of the damping it is easy to control the heat treatment of steel, and if necessary tempering can be conveniently supervised.

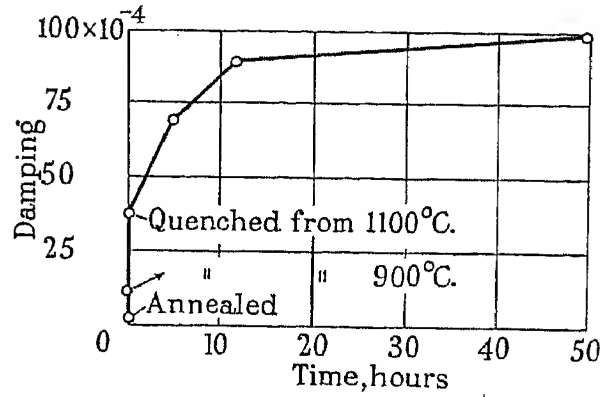


Fig. 16

## INTERCRYSTALLINE CORROSION

The measurement of damping constitutes an ideal means for the study of intercrystalline corrosion. This process, which is always associated with a loss of cohesion at the grain boundaries, increases the damping to an extraordinary extent. The sensitivity of a material to corrosion can be detected even a few minutes after the beginning of attack by a corrosive chemical. A not insignificant advantage, in comparison with other methods, is that the whole course of corrosion can be followed on a single test-piece. For this reason the amount of material required is very small, as is the

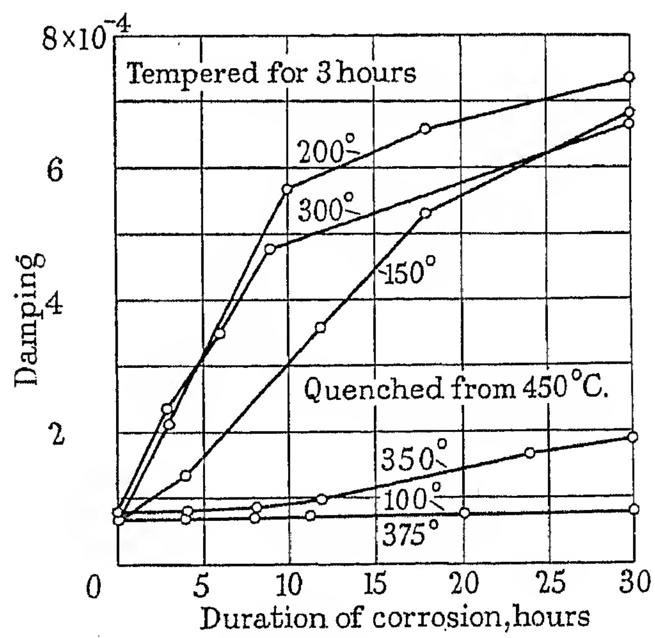


Fig. 17

amount of experimental apparatus required to carry out the corrosion. By simultaneous measurement of the natural frequency and the damping, a quantitative estimate can be made of the corrosion which has occurred. It is known that V2A steel which has been quenched from 1 050° C. and subsequently tempered at 600° C., is liable to intercrystalline corrosion by an acid solution of copper sulphate. After attack for 30 minutes, the damping increases by over 100 per cent, while the tensile

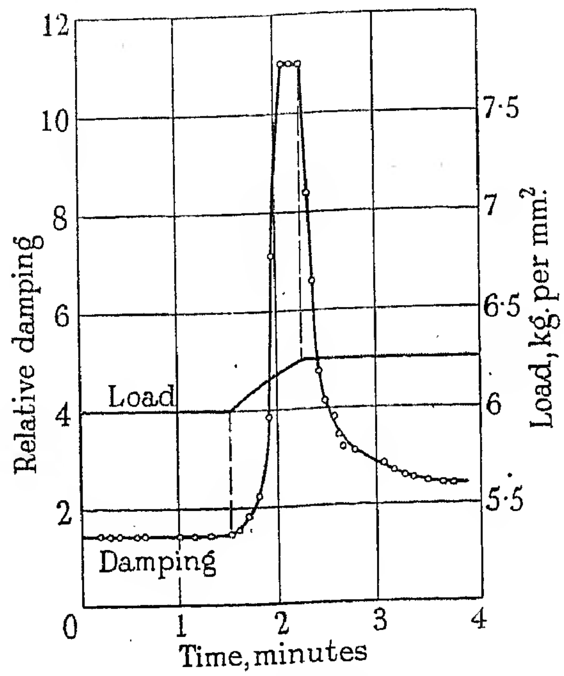


**Fig. 18.**—Damping of pure aluminium during increasing load, and recovery.

strength decreases by 9 per cent. A V2A steel which had not been tempered after quenching, and was thus not liable to intercrystalline corrosion, showed constant damping after several hundred hours. The variation of the damping of an aluminium-magnesium alloy containing 11 per cent of magnesium which had been quenched from 450° and attacked by salt solution, is illustrated by Fig. 17, which gives curves for different tempering temperatures. It is obvious that, with increasing tempering temperatures, the corrodibility attains a maximum at 200° C., in agreement with other investigations.

## TECHNICAL INVESTIGATIONS

This paper would be incomplete were stress not laid on one very promising field of inquiry. By using the above-described apparatus to obtain direct readings of the damping, it becomes possible to measure rapid changes in damping, as, for instance, changes in the damping of various materials during tensile tests. The stresses occurring during vibration are roughly 1/100 000 of the static forces acting in the tensile test. Thus, Fig. 18 illustrates the behaviour of a bar of pure aluminium which had been annealed at 350° C. and tested in the plastic range during and after the application of a load of 0·5 kg. per mm.²

During the application of the load the damping increased 10 times in a fraction of a minute, but after loading it fell exponentially to the original value. The dependence of the damping of the same material on the rate of strain is seen, and the behaviour of the damping in the transition from the elastic to the plastic range is most instructive.

## CONCLUSION

In the space available, it is possible only to mention a few of the researches which have been carried out, but the choice made will serve to show that the method of measurement described provides an important aid to the determination of the state of materials. It is important to note that the damping and the modulus of elasticity are quantities which, in contrast to many other technical values, possess an exact physical meaning.

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[The discussion on this paper will be found on page 580.]

# NON-DESTRUCTIVE TESTING IN THE U.S.A.

By H. H. LESTER, R. L. SANFORD, and N. L. MOCHEL.*

(*Paper received 23rd September, and read at a meeting arranged by the* JOINT COMMITTEE ON MATERIALS AND THEIR TESTING, *25th November*, 1938.)

## INTRODUCTION

The decision of the British Joint Committee on Materials and their Testing to hold a discussion on the subject of non-destructive testing would appear to be further evidence of a growing world-wide interest in methods that will permit of more completely testing the actual material or construction that man intends to use.

Such growing interest would almost imply that non-destructive testing is something quite new. While it is true that some methods in use are of recent development, and there is much activity in the development of new methods in many fields of industrial activity, it is also true that many of our present methods of non-destructive testing have been in restricted use for many years, but only recently has there been any widespread adoption of some of them. Industry is often very slow in adopting some of these more searching tests, and there are obvious reasons for this condition.

Usually, non-destructive test methods are originally developed for some rather special or limited application. Naturally, some methods never get beyond that first field of use. Others are of such nature that they quickly pass from a restricted field of use into broad or general adoption. Other methods may be in existence for years, and used but little or not at all, only to be picked up and used widely when design and operating conditions, such as speed, pressures, and temperatures, require or justify such practices.

Once these methods become developed and known, there is a moral responsibility on the part of the manufacturer or consumer to have these methods at hand, ready to use when the application involved justifies their use, whether it be a matter of safety to life or property, the integrity of product, or purely a matter of economy.

Some non-destructive testing methods have had an important part to play in the success that has attended certain engineering activities. The reliability of aviation engines and parts is in no small measure due to magnetic test methods that have prevented faulty parts from getting into service. Jacobus† has recently remarked that "radiographing was the turning point in the development of sound and reliable welding."

In the United States the term "non-destructive testing" has no fixed or narrow interpretation. It is rather broadly, even loosely, applied, ranging from very simple practical or empirical tests on the one hand to those of more complicated or technical nature on the other. In general, the use of the term involves the application of some overall test to the material or part actually to be used, to completely or partially determine its sufficiency for the intended service. It must test the material itself, not a sample of it. Sufficiency, as used above, may be a matter of soundness, tightness, freedom from injurious defect, freedom from harmful internal stresses, or a matter of proper hardness or desired structure, or any other feature upon which assurance is desired.

The term "non-destructive" of course implies that nothing is destroyed. This must be qualified to the extent that some tests, that have every right to be considered non-destructive tests, may bring destruction to faulty material or parts but have no effect whatsoever on satisfactory material. After all, faulty material is also rejected outright by other tests of a purely non-destructive nature, so that the net result is the same. Some tests, of course, leave rejected material available for correction.

The paper is divided into three parts, as requested by the British Joint Committee, as follows: Part 1—Radiographic Methods; Part 2—Magnetic and Electrical Methods; Part 3—Acoustical and General Methods.

## PART 1—RADIOGRAPHIC METHODS†

Routine radiographic inspection of castings began in the United States in 1922 with the installation of X-ray equipment at Watertown Arsenal for the examination of products of its own foundry and for the inspection of purchased material. Commercial industry began using the method in 1923 and 1924 for the examination of high-pressure steam valves and fittings and for oil refinery castings. In 1927 the aluminium industry began using it for control tests. The method was applied to the development and control of the welds of welded gun carriages in 1928. This is believed to be the first use of it for routine inspection and control in a weld shop. In 1930 the U.S. Navy accepted welded steam boilers manufactured under radiographic control. In 1931 the American Society of Mechanical Engineers recognized radiographically tested welds for unfired pressure vessels. Since that time radiography with X-rays has gone ahead rapidly. In 1931 there was one installation for pressure vessel-testing and five for other work, including the examination of castings. In 1936 these numbers had grown to 30 and 18 respectively. The latest estimate indicates that pressure-vessel manufacturers use 57 installations, and there are 31 installations devoted to

* The preparation of this paper was assigned by the American Society for Testing Materials to a committee composed of H. H. Lester, R. L. Sanford, and N. L. Mochel (Chairman). Part 1 was largely prepared by Mr. Lester (Watertown Arsenal), Part 2 by Mr. Sanford (National Bureau of Standards), and Part 3 by Mr. Mochel (Westinghouse Electric and Manufacturing Co.); but in each case there were suggestions, co-operation, and review by the other members of the committee.

† See Reference (1).

† Released for publication by the Chief of Ordnance of the U.S. Army. Statements and opinions are to be understood as individual expressions of their authors and not those of the Ordnance Department.

various other applications. Several companies have more than one X-ray installation, one company having 7. Five recent installations use voltages up to 400 kV. There are about six commercial testing laboratories that have X-ray equipment. No exact data are to hand regarding the quantity of films used, but it is roughly estimated that around 20 000 X-ray exposures are made annually.

One important paper in the 1936 X-ray Symposium* summarized radiography by gamma rays in the United States. In it the author points out that although some work was done in this field by Pilon and Laborde† in 1925, the first systematic studies in the method were made and the working out of practical technique was accomplished by Mehl, Barrett, and Doan, of the U.S. Naval Research Laboratory, in 1928.‡§ Typical examples are given illustrating the wide variety of structures examined. These include ship castings, valves and fittings for power plants and oil refineries, turbine casings, penstock piping, gun carriages, oil refinery towers, and others. Complete details of technique are given for the use of the method.

There has been no great change in the situation since Mochel's paper was written. Radium is used principally for the inspection of castings. The U.S. Navy is the largest user. It owns the large total of 2 965 mg. of radium divided into 11 units. These are used in various naval establishments and also in foundries that manufacture on navy orders. Two or three commercial companies own radium and there is one company that rents radium and radon for industrial radiography.

The situation with regard to the application of radiography to other than metal products has been described in another of the 1936 Symposium papers.‖ These applications have included such objects as wireless valves, telephone units, reinforced concrete, built-up mica, plastics, asbestos board, canned food, candy, and even hams. There seems to be a very broad field for such possible uses of the method. As yet routine examinations have been confined to plastic gears and radio and telephone parts.

### Radiography in the Foundry

A survey conducted in 1938 by C. W. Briggs of the U.S. Naval Research Laboratory for the benefit of the American Foundrymen's Association disclosed, among other things, the fact that only 5 foundries out of the 251 approached were using radiography for the development and control of manufacturing processes. Fourteen others come in contact with it through acceptance tests. In the 16 years that the method has been in industrial use in this country, only 2 per cent of the foundries have adopted it as a production tool and only 8 per cent have had to meet radiographic acceptance tests.

These low percentage figures do not represent lack of interest. They probably do indicate roughly the extent of present practicable applicability.

The method has been found to apply chiefly to three general classes of castings:—

(1) Castings that have to withstand high stresses or that have highly stressed sections. Cast gun cradles are examples.

(2) Castings that may not be highly stressed but whose unexpected failure might cause losses far in excess of the value of the casting. Some aluminium castings that go into aeroplane constructions, and castings that support the external propeller bearing on some ships, may be cited as examples.

(3) Castings that require extensive machining. Some castings used in the construction of gun carriages are illustrative; one casting, for example, costs $1 200 to finish machine from the rough, while the necessary X-ray pictures cost only $28. In some 50 castings examined there were no rejections, but about 60 per cent had defects requiring repair. Many of the castings would have been rejected if the defects had been found in late stages of machining.

Since the majority of castings fall outside of these somewhat narrow groups, there is really only a relatively small percentage of castings to which radiographic study can be applied economically. However, there is a present interest in extending radiographic development to castings where essential soundness may not be mandatory but is desirable. This interest is awakened partly by the growing competition of weldments and other casting substitutes, and the desire on the part of manufacturers to improve their products in a campaign to retain their market.

In Briggs's survey, 27 stated that they hesitated to use radiographic examination because of the cost of equipment, and 21 because of the cost of radiographic examination. The expense seemed to be the most important deterrent. This is greater than some realize. In straight inspection work, practically the whole cost involved is that of getting the negatives. Where used as a tool in development work the situation is different. One earnest foundry metallurgist remarked in discussing the subject, "It is not the cost of X-raying that bothers us, it is the probable cost of the consequences." In work of this sort negatives are studied very carefully by metallurgists or other highly trained personnel.

Defects are analysed from the evidence contained in the negatives and from all other known metallurgical facts. Fig. 1 is illustrative. In this particular case, a company making heat-treating equipment began a study of certain of its products with the idea that the elimination of porosity known to exist might increase their service life. A casting was X-rayed completely. Because it was scheduled for shipment and could not be held for study, a wooden framework was constructed simulating the shape of the casting. This was covered with translucent cloth and the negative was attached to the model which was illuminated from within. Fig. 1(*a*) shows the casting, while (*b*) and (*c*) show two views of the model. These pictures were posed at the request of one of the authors, but are truly representative of the way this particular company is using radiographic tests. Whether a model is used, or whether the casting is studied directly, the complete utilization of the information contained within the negative involves elaborate and expensive investigation and experimentation. Whether or not the procedure is justified depends upon the value of the results obtained. In most cases,

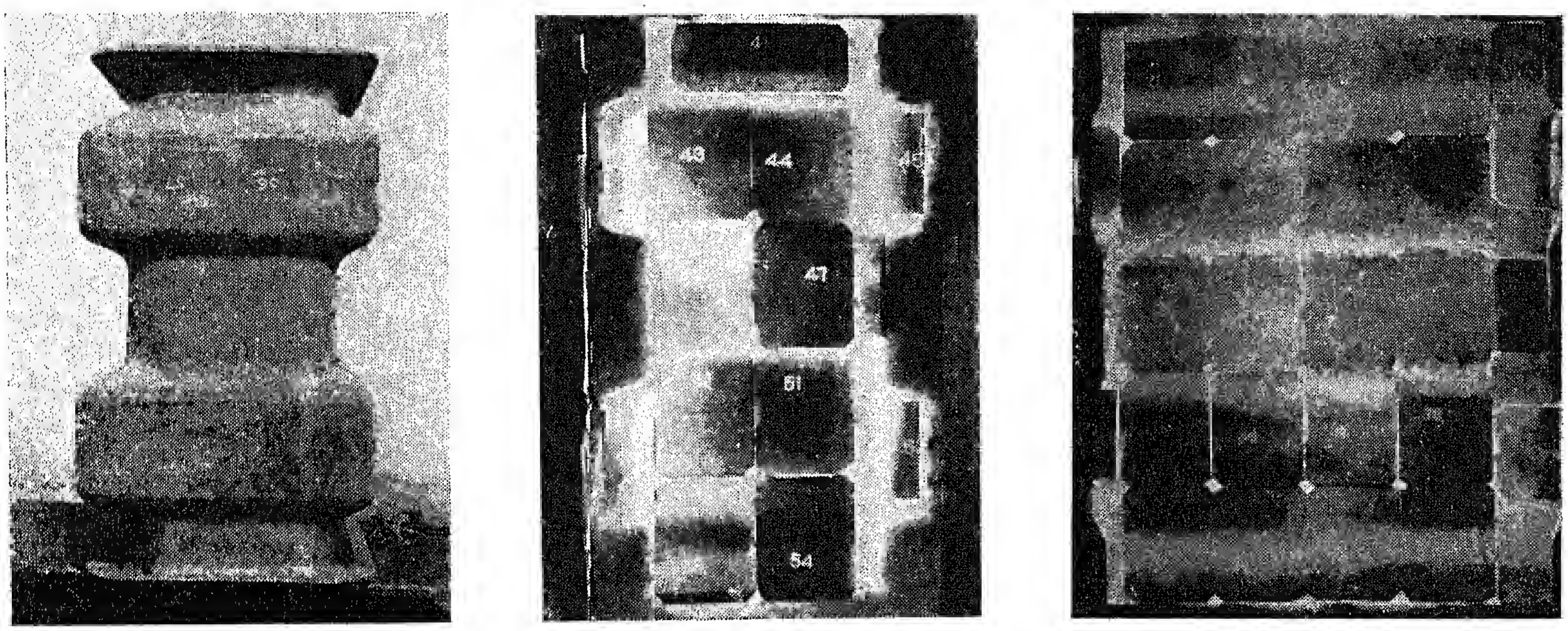
* See Reference (2). † *Ibid.*, (3). ‡ *Ibid.*, (4). § *Ibid.*, (5). ‖ *Ibid.*, (6).

development research does pay fair dividends on a considerable investment.

Another 1938 survey conducted for the benefit of the radiographic committee of the American Society for Testing Materials, to secure evidence as to whether or not there was a general confidence on the part of both producers and consumers in the results of radiographic inspection, revealed that those who have had direct experience with the method, both consumers and producers, have great confidence in it. The preponderance of opinion was to the effect that, within the scope of their sensitivity, radiographic tests properly carried out have not failed to reveal existing defects. Various reasons for not using the tests have been based upon lack of familiarity with them, fear of incorrect interpretations by unskilled personnel, distrust of innovations that might mean the adoption of new and unfamiliar standards of soundness, and expense. Probably the cost of testing is the most important item that has prevented wider use of the method.

In one of the recent surveys, the opinion was expressed that the use of radiographic tests has not resulted in marked improvement in the quality of castings. This has been the observation of one of the authors in testing purchased material for the Army Ordnance. It has been the experience of another of the authors that some improvement has resulted with some suppliers and little or no improvement with others. It is true that where foundries have only sporadic contacts with radiography through acceptance tests, there has been no particular improvement in casting quality resulting from the tests. On the other hand, where large enough values have been involved to justify the expense of studies to improve foundry procedures, the imposition of radiographic acceptance tests has been successful in bringing about improvements in manufacturing methods. Under these circumstances the radiographic tests are used really for development and control, since the negatives of rejected castings are studied and the results used in making successive attempts at improvement. It is understood that foundries making large castings used by the U.S. Navy have received considerable benefit in this way.

Recent tests (described below) have demonstrated that gamma graphs are somewhat less sensitive than X-ographs, the test negatives revealing a "cavity" 0·05 in. deep and 0·20 in. in diameter through 3 in. of steel, while X-rays showed under the same conditions of testing a "cavity" 0·03 in. deep and 0·03 in. in diameter. Gamma graphs cannot be relied upon to reveal fine cracks, but they are quite sensitive enough to show the porosity conditions that are of most interest to the foundry metallurgist. It is predicted that they will grow in popularity for the testing of large castings, partly because large values are involved. The expense of testing is relatively small compared with the value of the casting, and the value of the results is correspondingly great. The economy of the tests is more easily demonstrated under such conditions.




(*a*) The casting. (*b*) Model with films attached: end view. (*c*) Model (side view) showing porosity conditions.

**Fig. 1.**—Example of a method of analysis of radiographic films.

### Radiography in the Weld Shop

The use of radiographic testing for the routine development and control of industrial welding started in America with its application to fusion-welded gun carriages at Waterton Arsenal in 1928. The real impetus to this application came in 1930 with the adoption by the Navy of radiographically inspected welding for steam boilers, and the similar recognition in 1931 by The American Society of Mechanical Engineers in its Boiler Construction Code. Makers of pressure vessels of various kinds very promptly took up welding and also radiography. The latter has become an essential tool in manufacture.

One of the very great services performed for the testing methods was the defining in the A.S.M.E. Boiler Construction Code of definite standards of soundness to which manufacturers had to build. Porosity conditions were defined by pictures. Rejectable defects such as

cracks and unfused regions were specifically designated, and tolerable limits were established for slag inclusions. Other provisions had to do with the distance away from the work of the X-ray target, the surface condition of the weld, the type and method of using sensitivity gauges, etc.

The original code provisions have undergone revisions and are still being revised, but they introduced definiteness into radiographic testing and did much to remove one of the most important objections to the method—the dependence of interpretation on the personal estimation of an individual. In 1935 the Bureau of Engineering of the U.S. Navy established radiographic standards for Class A-1 welds for its own work. These are defined by 18 type pictures covering the range of acceptable and non-acceptable conditions. The Navy standards of porosity have been ". . . adopted for the A.S.M.E. and for the Joint A.S.M.E.–A.P.I. Construction Codes for Unfired Pressure Vessels. . . ." Fig. 2 (see Plate 13, facing page 572) illustrates one of these standards, showing the limit of allowable porosity in Class A-1 welds.

While the standards referred to above have been of great assistance and are, no doubt, the best that could be made at the time, they are not regarded as perfect. They were chosen arbitrarily because there are no reliable data on the physical importance of defects seen in radiographic negatives. Cracks and crack-like defects are, of course, causes for rejection, but it is not known how seriously various porosity conditions affect physical properties. These are selected as representing the highest soundness characteristics from the standpoint of porosity that is commercially practicable. An investigation of the problem of the evaluation of physical defects is now being undertaken through the co-operative effort of interested industrial societies.

Outside of the pressure-vessel field, radiographic testing of welds is utilized by the Army and Navy and by commercial concerns manufacturing ordnance weldments. In these applications not all of the welds are X-rayed. In some structures all of the important ones are and there is random examination of other welds. In other cases a certain percentage of pieces is examined completely.

There are various commercial structures outside of Army and Navy weldments to which the method has been applied. Gamma rays have been used in cases where, for various reasons, X-rays could not be employed. The latter are preferred for the examination of welds because of their greater sensitiveness and because, for most shop applications, they save time.

While inspection is the emphasized feature, in the weld shop X-ray examination is carried out mainly by the producer and is used as much for development and control as for final inspection. The individual welder is qualified partly on the basis of radiographic tests. His production work is checked daily by X-ray pictures. This supervision gives close control, reduces final inspection to a formality, and practically eliminates large losses through final rejections.*

It is interesting to note that, according to opinions expressed in one of the 1938 surveys mentioned above, the producers and consumers alike are enthusiastically in favour of X-ray tests for weldments. It was brought out that to date there is no record of failure of a weld manufactured under X-ray control and stress relieved. This is a rather strong endorsement of X-ray control.

One interesting application* that really comes under the head of weld applications is the examination of composite gold plate where unfused regions between the $\frac{1}{8}$-in. gold sheet and the base plate are detected before rolling the block to final thinness. One important company examines all of its brazed composite plates by X-ray.

### Industrial Radiographic Committees

Progress in the application of radiography to the problems of industry has been facilitated by various committees devoted to such interests. The A.S.T.M. was the first to recognize the method and has had a sub-committee on X-ray metallography since about 1925. Other groups are the Radiographic Committee of A.F.A., the Joint American Society of Mechanical Engineers—American Petroleum Institute Committee on Radiography of Welds, and the Sub-committee on Non-destructive Tests of the Welding Research Committee under the Engineering Foundation. During the past year the A.S.T.M. has reorganized its work on radiography, formerly handled as a sub-committee on X-ray metallography, and has set up a new standing committee on radiography. This new body has a membership of about 45. It aims to be broadly representative of all radiographic interests. The membership includes important representation from each of the other radiographic committees. There are six sub-committees dealing with "Castings," "Welds," "Technical Research," "Correlated Abstracts," "Safety," and "Technical Programmes," respectively. The first technical programme sponsored by the committee was presented at the 1938 Annual Meeting of the A.S.T.M.

The casting sub-committee, under C. W. Briggs, has mapped out a comprehensive programme involving extensive co-operative effort among the organizations represented. It contemplates pictorial definitions of defects, education of consumers to porosity conditions inherent to design, a study of possible economical applications of the method to foundry problems, and various other details leading eventually to a sane basis for the formulation of radiographic specifications for the manufacture of steel castings.

The welding sub-committee also has a programme under way, the chief feature of which is the evaluation in terms of physical quantities of the defects seen in radiographic negatives.

The sub-committee on technical research, under the leadership of H. E. Seemann, has already contributed four worthwhile papers.† They are by individuals of the committee and do not represent co-operative effort.

One broad purpose of the activities of the research committee is to work for improvements in radiographic negatives. Eventually it is hoped that they will have the clarity and detail of good photographs. Such pictures can be produced now in some kinds of medical work and when examining thin metal sections. For the

* The "Welding Handbook" issued in 1938 by the American Welding Society contains a chapter on "Radiography" that gives a fairly complete picture of the radiography of weldments.

* See Reference (7).

† *Ibid.*, (8), (9), (10), (11).

most part, however, industrial radiographs are very far from ideal. A first approach to the general problem is obviously a systematic study of the various factors that influence the quality of negatives. The four papers referred to were directed along this line. One considered conditions of image formation* with regard to different distances between source of radiation, specimen, and film. The other three were devoted to the problem of intensifying screens and to the study of secondary radiation. One of them,† by the chairman of the sub-committee, was written before the sub-committee was organized. It is included as a committee contribution because it is a preliminary study of the factors involved in intensification. A second report‡ on the screen problem is among the annual meeting papers. Others will no doubt follow. In the 1937 report§ Seemann discussed the two factors involved in the intensifying action, direct electron action and fluorescent radiation. He has devised an ingenious method for evaluating the two effects and offers quantitative measurements of them. The radiation effect is shown to be due to the characteristic K radiation of lead. With the usual arrangement of front and back screens and double-coated films, it is found that the electron effect accounts for 84 per cent of the intensifying action for the front screen and 75 per cent for the back screen.

A preliminary study of the effect of lead foil in reducing objectionably secondary radiation is also included in this paper. A further development of this feature forms the substance of another of the 1938 papers.‖

In the 1938 paper on intensifying screens¶ the relative efficiencies of calcium-tungstate and lead-foil screens are compared for gamma-ray radiography. Calcium-tungstate screens were found to give shorter exposure times, but the blackening of the film was not consistent with an inverse-square law for the intensity of radiation from the gamma-ray source. Lead screens, though slower, gave more consistent results and better definition.

The problem of secondary radiation from the portion of the specimen adjacent to the film is probably the most important one up for solution to-day. It is particularly vexatious in the X-raying of metal specimens above $1\frac{1}{2}$-in. thick. Secondary radiation is the re-radiation by the specimen due to its absorption of some of the primary radiation that proceeds from the X-ray tube. The optical density of the negative comes partly from the primary radiation, which alone is responsible for image formation, and partly from the secondary radiation, which produces a general fog over the negative and obscures the images that may be present from the primary beam.

The solution of the secondary radiation problem is a present active consideration of the research sub-committee. Preliminary studies were reported in the 1937 paper** referred to above. In this paper it is pointed out that the secondary radiation is ordinarily of longer wavelength than the primary, and that differential absorption of primary and secondary radiations is possible. Quantitative measurements are given. In the 1938 paper,†† by the same author, the effects of secondary radiation are discussed and a method of measuring this quantity is described. In the experimental results obtained it was found that almost one-half of the secondary radiation could be removed by filtering through lead foil. An almost linear increase in secondary radiation with increase in thickness of material was found, and there was no appreciable variation of secondary radiation with variation of potential on the X-ray tube for a given specimen. These experiments were carried out with aluminium. It is rather probable that the results will be different for steel.

* See References (10). † *Ibid.*, (8). ‡ *Ibid.*, (11). § *Ibid.*, (8).
‖ *Ibid.*, (9). ¶ *Ibid.*, (11). ** *Ibid.*, (8). †† *Ibid.*, (9).

The joint A.S.M.E.–A.P.I. committee for the radiography of welds has been in existence some years. To it come radiographic questions that concern the A.S.M.E. and A.P.I. construction codes for welded pressure-vessels. A report presented in June* concerned penetrameters and a test block. The penetrameter, hitherto prescribed in the code, is a piece of steel $\frac{1}{2}$ in. wide and arranged in steps $\frac{1}{2}$ in. long and of graded thicknesses so that the thickness of one step is 2 per cent of the thickness of the metal being radiographed. Each step contains a hole $\frac{3}{8}$ inch in diameter drilled through the $\frac{1}{2}$-in. square face. The device is placed alongside the weld being radiographed and its image appears in the negative. If the hole corresponding to the 2 per cent step shows, it is assumed that all cavities in the metal of equal or greater thickness dimensions are shown. It was supposed to be a sensitivity gauge. In practice it was discovered that cavities greater than 2 per cent sometimes did not show in the negatives although penetrameter holes corresponding to as low as $\frac{3}{4}$ or even $\frac{1}{2}$ per cent could be shown. There was objection also because the regular gradation of steps with the equal spacing of holes led to optical illusion, so that the 2 per cent image was often " seen " when it really was not visible.

The difficulty with this penetrameter was found to lie in the fact that the " area effect " was neglected. The discernibility of an image in the negative depends upon its blackness relative to the background, the sharpness of its outline, and its area. The holes in this penetrameter are too large.

The penetrameter has been regarded as more than a sensitivity gauge. It has been the guarantee to the purchaser of the weldment that the picture in which it is seen was properly taken. There are differences in equipment, in technique, and in the skill or carefulness of operators. There is a question as to whether the penetrameter goes far enough in giving information as to correct radiographic procedures. Also the penetrameter cannot be used easily as a sensitivity gauge.

A test block was suggested† as a tool to supplement the penetrameter and as a device that could be used in studying many of the variables that enter into the clear depiction of radiographic images. A definition offered by the penetrameter sub-committee was: " The test block is a device made up of carbon steel plates, some of which contain artificial defects, that may be used to determine whether or not a given radiographic equipment used according to a given procedure does in fact produce radiographic negatives of passable quality."

* Not published—A résumé will be presented as a report to Committee E–7 on Radiographic Testing of A.S.T.M. and will probably be available through that Society.

† The test-block idea originated with C. A. Adams, chairman of the A.S.M.E.-A.P.I. Committee on the Radiography of Fusion-Welded Joints.

The use of the test block was defined elaborately, one clause specifying that "the test block used with a properly selected penetrameter may be employed to determine the limits of sensitivity that can be obtained from the equipment and technique."

In another clause it is specified that ". . . the sensitivity found with the test block shall not be regarded as equivalent to that obtained in routine testing where the results are affected by various factors such as difficulties in positioning, roughness of under surface, etc."

The above definitions are quoted from a report of the sub-committee to which the matters of the penetrameter and test block were referred. This sub-committee proposed a penetrameter of uniform thickness equal to 1 per cent and containing three holes whose diameters were 1, 2, and 4 per cent of the thickness of the metal to be tested.

A test block, together with penetrameters of the type suggested, was sent to 6 laboratories represented in the committee membership for study and experiment. A set of 9 experiments, involving different combinations of locations of defects in the test block, were carried out for the block built up to 1-, 2-, and 3-in. heights, respectively. These 27 exposures were made in each laboratory. No restrictions were placed on the procedures except that the film-to-target distance was fixed at 30 in., and it was requested that the film density should be the same as that of a film supplied for the purpose of comparison. One laboratory tested with gamma rays as well as X-rays.

Each laboratory reported results in detail, and, after completion of all of the tests, the films were assembled at one laboratory and analysed by two men trained for negative reading. These men worked independently, each man reading all films. Differences of interpretation were settled with the assistance of a third man.

The smallest holes in the 1 per cent penetrameters were expected to be practically beyond the limits of detectability.

The results of the tests with the 2-in. block showed that no laboratory brought out the smallest hole, which was 0·02 in. deep and 0·02 in. diameter. All except one showed the second hole (0·02 in. deep, 0·04 in. diameter). One set of films showed the large hole (0·02 in. deep, 0·08 in. diameter). It was surprising to find that the gamma-ray films showed the No. 2 hole of the 1 per cent penetrameter. No Bucky diaphragms were used in the 2-in. set-up, but lead filters were used in at least one laboratory.

There were 8 sets of films made in the 3-in. tests, one laboratory testing with and without the Bucky diaphragms and one testing with both X-rays and gamma rays. Three sets were made using 400 kV on the X-ray tube, two sets were made with 250 kV, and two with 220 kV. Two sets of films were made with the assistance of a Bucky diaphragm and, using 400 kV, brought out the smallest hole in the 1 per cent penetrameter (0·03 in. deep, 0·03 in. diameter). One using a Bucky diaphragm and 400 kV brought out the No. 2 hole (0·03 in. deep, 0·66 in. diameter). Three sets without the Bucky diaphragm and with 220 kV brought out the No. 1 hole (0·03 in. deep, 0·12 in. diameter). One set without the Bucky diaphragm and with 250 kV did not show any holes in the 1 per cent penetrameter but did show the No. 3 hole in the 1·33 per cent penetrameter (0·04 in. deep, 0·04 in. diameter). The gamma-ray films showed the No. 1 hole in the 1·67 per cent penetrameter (0·05 in. deep, 0·20 in. diameter).

These results probably show the limits of sensitivity for industrial laboratories in this country. They are not practical limits. They show what can be done under very favourable conditions but not what one can expect under usual shop working conditions. The images of such small holes are too faint for easy detection, and they lack sharpness. Even those made with Bucky diaphragms were not satisfactory from this standpoint.

It was found necessary in order to get consistent readings, and indeed to see some of the images, to read the negatives in a darkened room supplied with illuminators equipped with controlled illumination. That is, all the light that came to the eye came through the film, and its intensity was adjusted to the point of greatest acuity of vision. The film-reading room is regularly equipped in this manner in some laboratories.

In addition to the penetrameters, the test-block assembly included one plate that contained a crack system. This was made by laying down a weld under conditions that would cause cracking. The plate was then planed down to $\frac{1}{8}$ in. thickness and cut so as to place the cracks in one corner. The weld cracked generously in a complicated pattern but few of the branches penetrated the complete thickness of the plate and, due to the grinding, most of them were rather shallow.

As was expected, the films for the 1-in. set-up detected the main crack system in its entirety except that the gamma-ray test revealed most but not all of it. There was a minor crack system separate from the main one at the junction of the weld with the plate metal that had been removed mostly in grinding. Four of the 7 sets of films showed the greater part of this system. One 400-kV set did not show it, while the 250-kV set and the gamma-ray set also did not show it.

It was the general experience that as the crack system was moved closer to the film in its location in the test block there was an improvement in the definition. However, the definition was fairly good in both the remote and the near locations.

For the 2-in. test-block arrangement only the gamma-ray set of films failed to reveal any of the main crack system. One 400-kV set showed nearly all of it, the others only the more important branches. None of the films showed any of the minor crack system.

For the 3-in. arrangement the main branches of the principal crack system were shown in 5 of the 8 sets of films submitted. The pictures taken with 400 kV and Bucky diaphragms were superior to the others. The gamma-ray set showed none of the cracks. The 250-kV set and one 220-kV set also failed to show any of the cracks. Images were faint but the definition was fairly good. In this series, as with others, there was improvement of the pictures as the location of the cracks was moved closer to the film.

One question of importance in practical inspection relates to the ability of individual radiographic labora-

tories to produce radiographs of a quality that will insure that detectable defects are revealed. The inspector must have confidence in the negatives. The test block was intended to provide a method for determining the ability of a given laboratory to produce negatives of the quality required by inspection. The question, so far as the test block is concerned, is whether this device can be used to rate the relative quality of the negatives produced in various laboratories.

On the basis of the detectability of images, the various participating laboratories were given relative ratings as to the quality of their negatives. Judging by these ratings, one of the organizations that has the best obtainable equipment and highly skilled operators, and that takes justifiable pride in the quality of its work, fell almost to the bottom of the list. This organization was the first one to perform the experimental tests, and carried them out in the spirit originally intended, that is, with the exact shop routine and without any additional care over what would be given to ordinary production work. As the test block went from place to place, there developed more and more a spirit of competition so that for the most part the ratings represented the best that each organization was capable of, rather than the average quality that might be expected in production work. It is of value to determine the best possible results. From them one might qualify a laboratory in the sense that a welder is qualified, but they may be misleading to an inspector in that they do not indicate the actual sensitivities in the films that he is called upon to examine.

There are questions as to the possible abuse of the test-block results, in that by means of it manufacturers might be held to unnecessarily high (and therefore unnecessarily expensive) standards of workmanship. For these and other reasons the committee voted to refer the test block back to the sub-committee for further study.

The committee consideration of the penetrameter images obtained in the test-block experiments led to the conclusion that the images of a 1 per cent penetrameter with a minimum 1 per cent diameter hole is much too difficult to use in practical work. It was concluded that the essential purpose of the penetrameter, namely the assurance that the negative in which its image appears was made properly, could be accomplished as well with one whose images could be seen easily. The final recommendation specified a penetrameter made of material similar to that of the metal under test, the dimensions of which are $\frac{1}{2}$ in. wide, $1\frac{1}{2}$ in. long, of a thickness equal to 2 per cent of the metal, and containing three drilled holes whose diameters are respectively 4, 6, and 8 per cent of the metal thickness. Provisions were made for the appearance in the image of the positive identification of the penetrameter used.

In the above an attempt has been made to sketch briefly, though incompletely, the development of radiographic testing in the United States and to present the trend of modern thought in this important field of non-destructive testing. Emphasis has been given to practical applications and to technological research of direct bearing on industrial usage. The authors desire to acknowledge the assistance of the General Alloys Co. of Boston in supplying the illustrations in Fig. 1, to the U.S. Navy Bureau of Engineering for permitting the use of unpublished data, and to C. W. Briggs, H. E. Seemann, G. E. Doan, and to the A.P.I.–A.S.M.E. Radiographic Committee, for the use of unpublished data.

## PART 2—MAGNETIC AND ELECTRICAL METHODS

### Magnetic Methods

In the United States the term " magnetic analysis " has been adopted to denote the use of magnetic methods for the investigation and inspection of materials with respect to properties other than magnetic, as distinguished from tests made for the sole purpose of determining magnetic properties. The idea of taking magnetic characteristics as criteria of mechanical quality is not new. As early as 1868, S. M. Saxby, in a paper* before the Institution of Naval Architects, described experiments in which he was able to detect certain defects and inhomogeneities in specimens of iron, including gun barrels, by means of a magnetic compass. Ten years later A. Herring, of Cohoes, N.Y., applied for a United States patent† for " Improvement in Ascertaining the Density and Tensile Strength of Iron and Steel by Magnetism," which was granted in 1879. His " improvement " constituted an extension of the principles used by Saxby and also employed a compass needle as the indicating element. William Metcalf,‡ in 1880, also considered the possibility of utilizing magnetic properties as an index of quality and read a paper before the American Institute of Mining Engineers. These early investigators were greatly hampered by imperfect knowledge not only with respect to magnetic phenomena, but also with regard to the structure and physical characteristics of iron and steel. It is only in relatively recent years that the fundamental principles have become sufficiently well understood to permit their practical application in industry.

The modern development of magnetic analysis in the United States dates back to the pioneer work of C. W. Burrows and F. P. Fahy, who, in the latter part of 1911, undertook at the National Bureau of Standards an investigation of the magnetic and mechanical properties of spring steel under the joint sponsorship of the Bureau and the Pennsylvania Railroad. This investigation was later extended to cover the applicability of magnetic analysis to various other forms of steel products and was carried on over a period of about 5 years. The results were published in the *Proceedings* of the American Society for Testing Materials in 1919.§

In 1918 the American Society for Testing Materials established Committee A-8 on Magnetic Analysis for the purpose of fostering the development and application of magnetic analysis in industry and of carrying out fundamental researches of a general nature. The committee served primarily as a clearing house for the interchange of ideas and experiences among its members, many of whom carried out individual investigations on various phases of the subject. This committee was recently merged with Committee A-6 on Magnetic Properties and now functions as a sub-committee of Committee A-6.

Since 1916, when Burrows published a summary‖ of

* See Reference (12).
† U.S. Patent No. 213197, March 11, 1879.
‡ See Reference (13).
§ *Ibid.*, (14).
‖ *Ibid.*, (15).

previous work on the correlation of magnetic and mechanical properties of magnetic materials, scores of papers on various phases of the subject have appeared in the technical literature. In the light of present knowledge it appears improbable that a universal relationship exists between the two sets of properties regardless of material. On the other hand, no exception has been recorded to the general principle that, for material of the same composition, two specimens having identical magnetic properties will be found to have the same mechanical characteristics and, further, that any treatment which alters the mechanical properties to a measurable extent at the same time changes the magnetic properties, though not necessarily to a corresponding degree. The nature of the changes is generally similar for different types of material, but this is not a universal rule as notable exceptions have been observed. Furthermore, certain secondary effects, particularly mechanical strain, exert an influence on magnetic properties out of all proportion to their effect on mechanical properties. These secondary effects constitute one of the major difficulties in the way of practical applications or the establishment of definite quantitative relationships. It must be recognized, therefore, that there are certain limits to the applicability of magnetic analysis imposed on the one hand by the physical principles involved and on the other hand by experimental difficulties. These limits cannot be stated definitely because the physical principles are not well understood and experimental technique is continually being improved. It may be remarked that the development and application of magnetic analysis has been retarded no less by the extravagant claims of over-optimistic enthusiasts than by the doubts of over-cautious sceptics.

Since it does not appear feasible to deduce the mechanical properties of a given piece of material directly from data on its magnetic properties, it becomes necessary in practice to compare its magnetic properties with those of another piece known to have the requisite mechanical properties which serves as a standard of quality. The amount of difference which can be tolerated is determined by experiment. Various methods of making such comparisons have been devised, several of which have been found to be commercially practicable and are in daily use. As a rule, only one magnetic characteristic is taken as the basis of comparison. This may be simply the magnetic permeability, some quantity such as residual induction or coercive force derived from the hysteresis loop, or the wave-form of an alternating induced voltage as determined by the shape of the hysteresis loop. Various inhomogeneities and flaws are also detected by abnormal magnetic leakage which they produce under proper experimental conditions. Methods have also been developed for measuring the thickness of nickel coatings on non-magnetic base metal, and of non-magnetic coatings on magnetic base metals. It is difficult to estimate with any reasonable degree of accuracy how extensively the methods of magnetic analysis are employed at the present time. Several suggested methods have either been found impracticable under commercial conditions or have not been developed to meet shop conditions. On the other hand, some of the most useful methods have never been described in the technical literature. Perhaps an idea of the general utility of magnetic analysis may be given by a brief description of a few typical examples.

One of the earliest successful applications of magnetic analysis is an apparatus for testing steam turbine bucket-wheel forgings developed by the General Electric Co. with the collaboration of Dr. Burrows.* The forging under test is slowly rotated on its own axis between the poles of a d.c. electromagnet, which can be adjusted to any given position on the radius of the circular forging. The magnetic flux traverses the air-gap between the pole-tips, in which air-gap the disc is rotated. Variations in magnetic quality of the material in this air-gap are indicated by an instrument connected to differential test-coils mounted on the poles of the electromagnet.

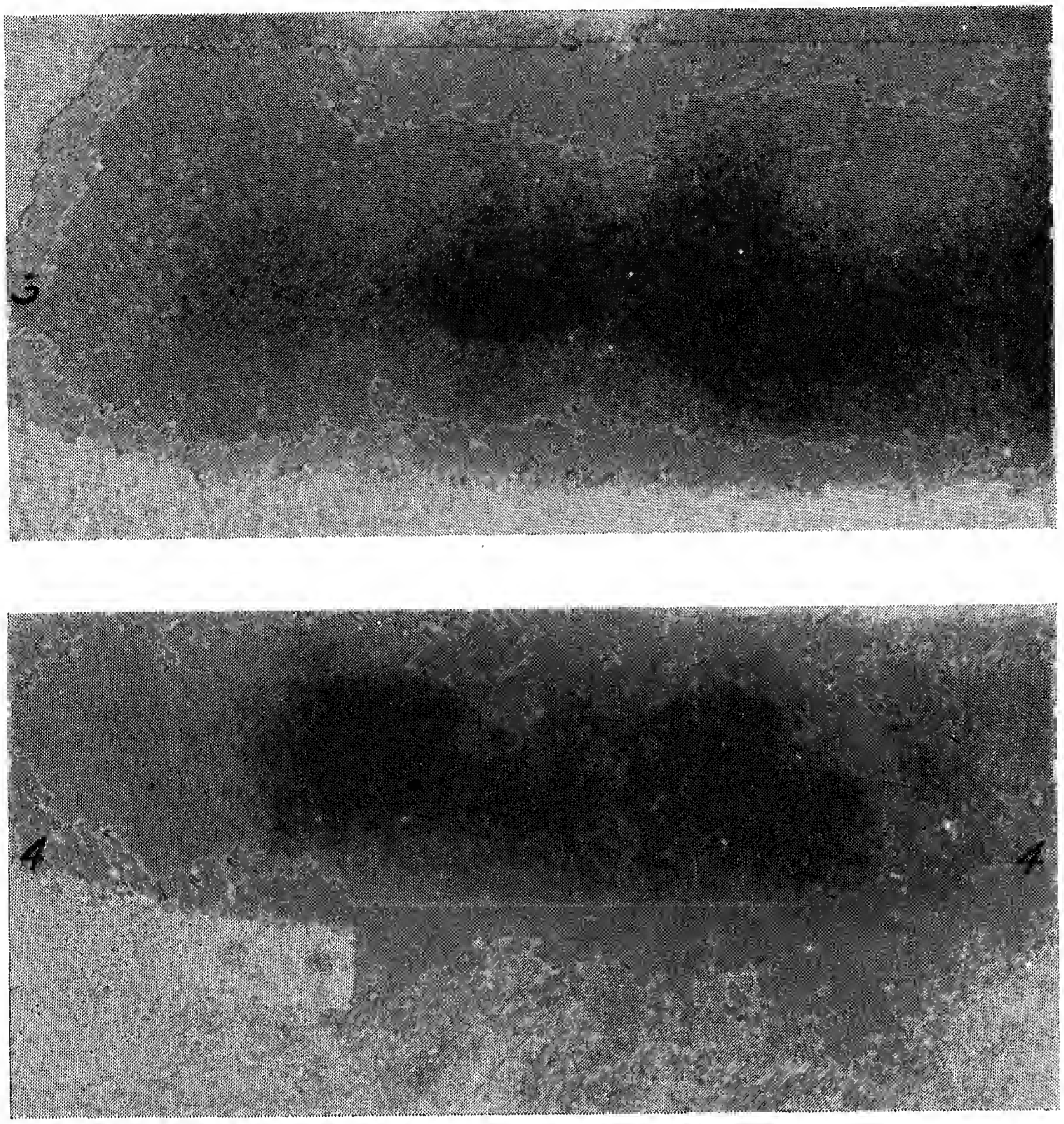
In the paper describing this apparatus† it is stated that forgings in which defects are indicated by the magnetic test are always given a visual examination even though they may be destroyed in taking the necessary specimens. Furthermore, the statement is made that "It is a significant fact that we have never had a magnetic indication of trouble without finding an adequate cause." Although rejections are very few, it is obviously very important that no defective piece be used in a finished turbine, since failures in service generally result in serious damage or even loss of life. The magnetic testing apparatus has been in constant use over a period of several years.

Although d.c. methods are usually best for fundamental investigations, it has been found that there are several advantages to be gained by using alternating current for routine inspection. It is possible, for instance, to obtain readings which depend upon the shape of the hysteresis loop, which often is a better indication of structural characteristics than simple permeability.

One company specializes in the inspection of steel and steel products by magnetic methods. Their apparatus‡ employs alternating current and operates on the comparison principle in which the material is compared magnetically with a standard of known quality. The method is best adapted to material of uniform section in relatively long lengths such as bars, tubes, sheet, and strips, but has also been applied to such products as bolts for aircraft and shafts for golf clubs.

In order to guarantee satisfactory and continuous operation and the incorporation of later improvements which are continually being developed, this company leases its apparatus to customers in preference to selling outright. In its original form the apparatus consisted of two exactly similar magnetizing coils within which were mounted search-coils, also alike, and connected in series, opposing. A suitable standard was inserted in one set of coils, and the material under test was passed through the other set. The wave-form of the difference in electromotive force induced in the two search-coils was indicated by an oscillograph. The wave-forms thus observed were then interpreted as indicative of differences between the properties or condition of the test material and the standard. Later improvements include the replacement of the oscillograph by indicating instruments and signal lamps, which improved the precision of the

* See Reference (16). † *Ibid.*, (16). ‡ *Ibid.*, (17).



(*a*) Borderline porosity—acceptable.

(*b*) Borderline porosity—not acceptable.

**Fig. 2.**—Radiographic standards for Class A1 welds.

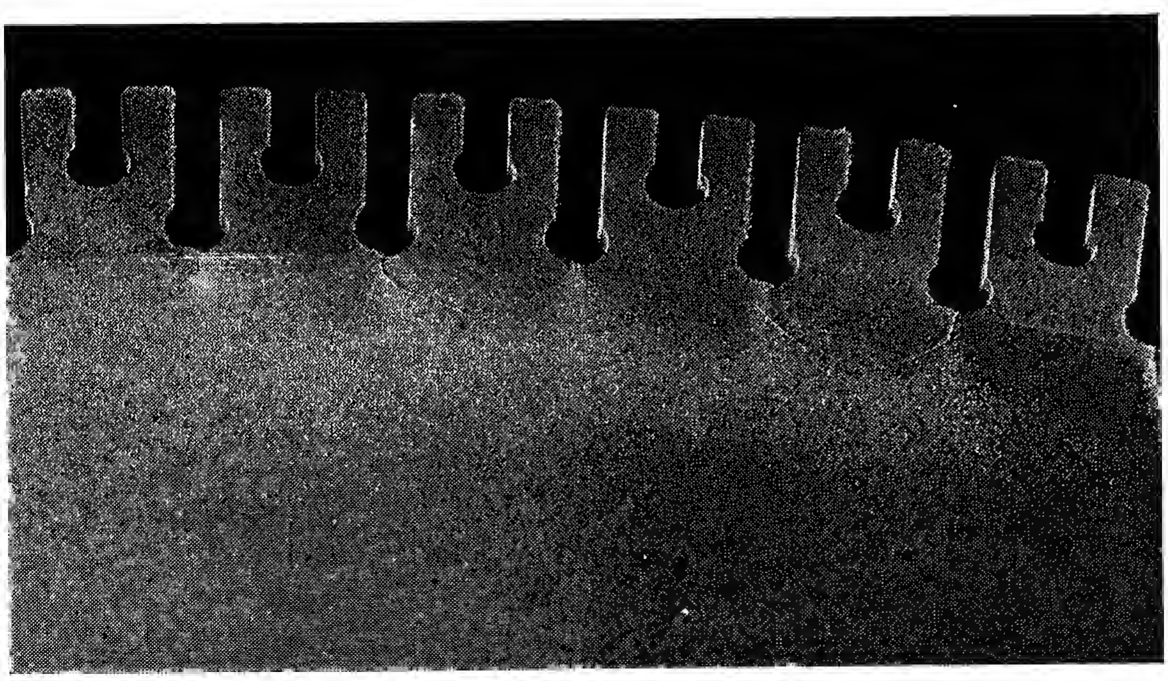


**Fig. 5.**—Cracks in turbine bucket-wheel forging revealed by Magnaflux method (Magnaflux Corporation).

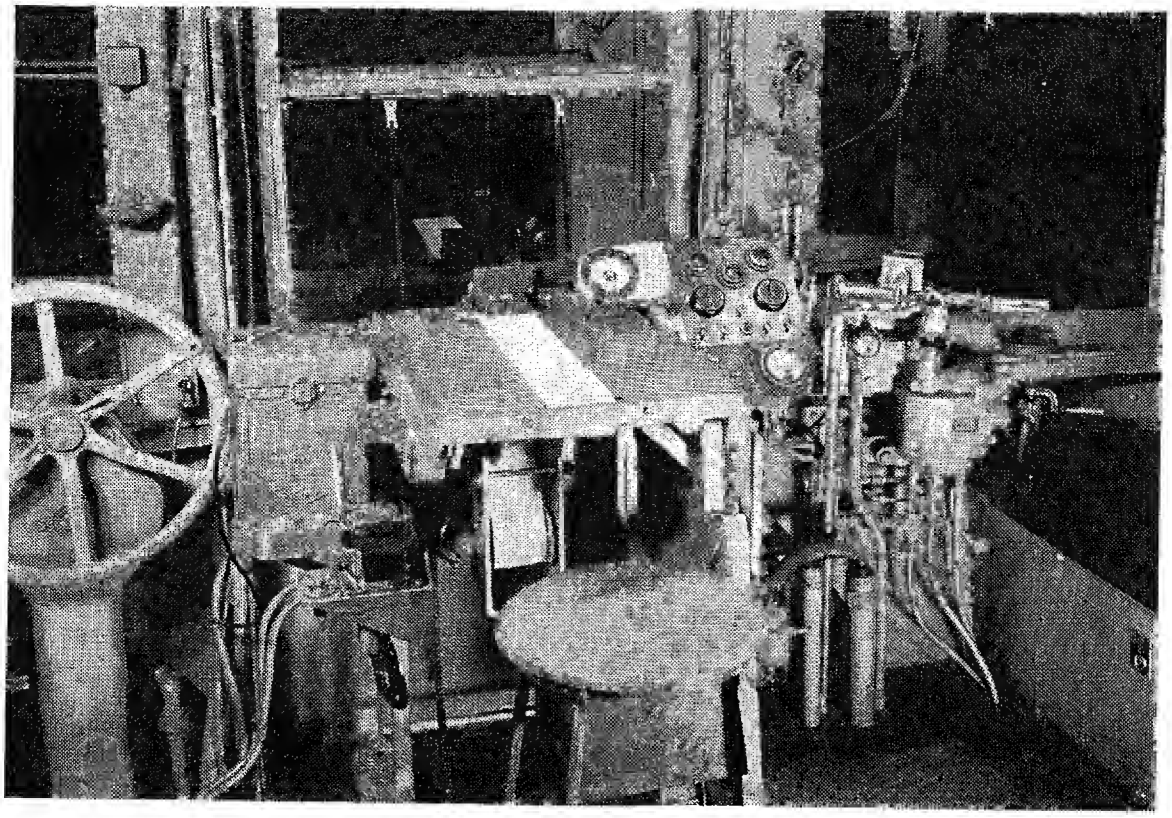


**Fig. 7.**—Record table and tape, Sperry detector car (Sperry Products, Inc.).

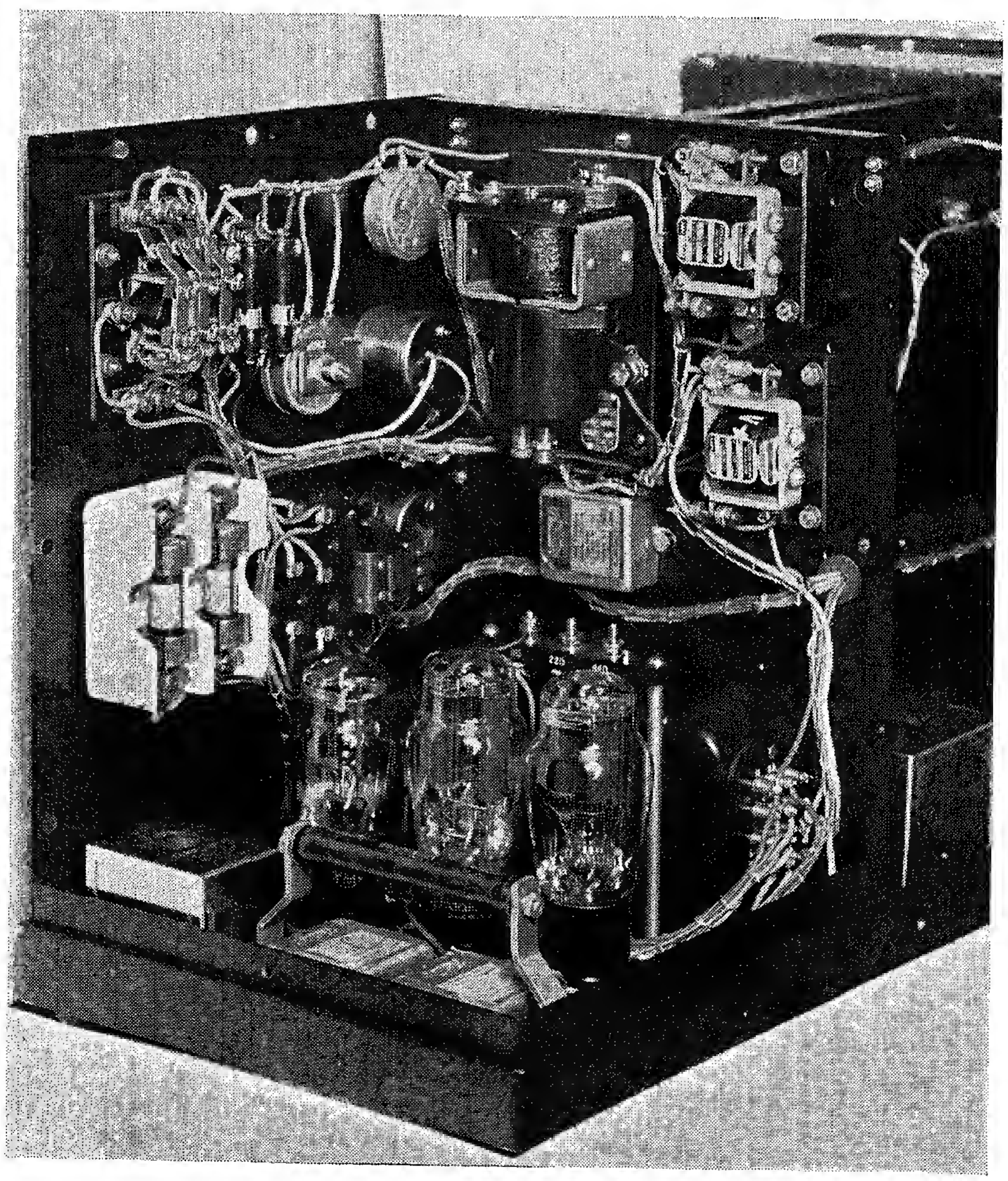


**Fig. 8.**—Interior of Ronay arcronograph (Rubicon Co.).

indications and speed of operation; the addition of filter circuits for differentiating between the various harmonics; and the substitution of electric standards for the original standard coil arrangement which had to be water-cooled to avoid undesirable temperature effects.

The apparatus (Fig. 3) is used to check bar stock for analysis, mechanical defects such as cracks, seams, and deep slivers, excessive segregations, and uniformity of structure as affected by heat treatment. Pipe and tubing are also inspected for quality of welds and uniformity of heat treatment.

The Magnetic Analysis Corporation give the following information showing the progressive increase in the quantity of bar stock inspected with their apparatus during the past few years:—

*Total Tonnage of Bar Stock Inspected*

| Year | Tons |
|---|---|
| 1932 | 2 000 |
| 1933 | 8 000 |
| 1934 | 21 000 |
| 1935 | 46 000 |
| 1936 | 63 000 |
| 1937 | 87 000 |

On account of the great diversity of products and manufacturing conditions which have to be met, no one type of apparatus is universally applicable. Each inspection problem must be considered individually in the light of the nature of the product and the requirements as to structure, freedom from defects, and manufacturing processes. As examples of different kinds of problems which have been met in practice, several types of apparatus may be cited. One company* has established a regular procedure for the study of new problems in which the material is magnetized with a suitable magnetizing winding using alternating current. The electromotive force induced in differential test-coils mounted within the magnetizing winding is fed into a harmonic analyser by which the magnitudes of the harmonics are measured. The phase relations of harmonics are observed by means of an oscillograph. By a study of the harmonics and their phase relations the type of apparatus required to meet the specific requirements is determined.

In this way apparatus was developed for the detection of defects in small-size boiler tubing, inhomogeneities in magnetic strip material, and imperfect lap welds in steel tubing. This equipment satisfactorily located defects not visible to the eye, and with automatic control very rapid inspection is accomplished.

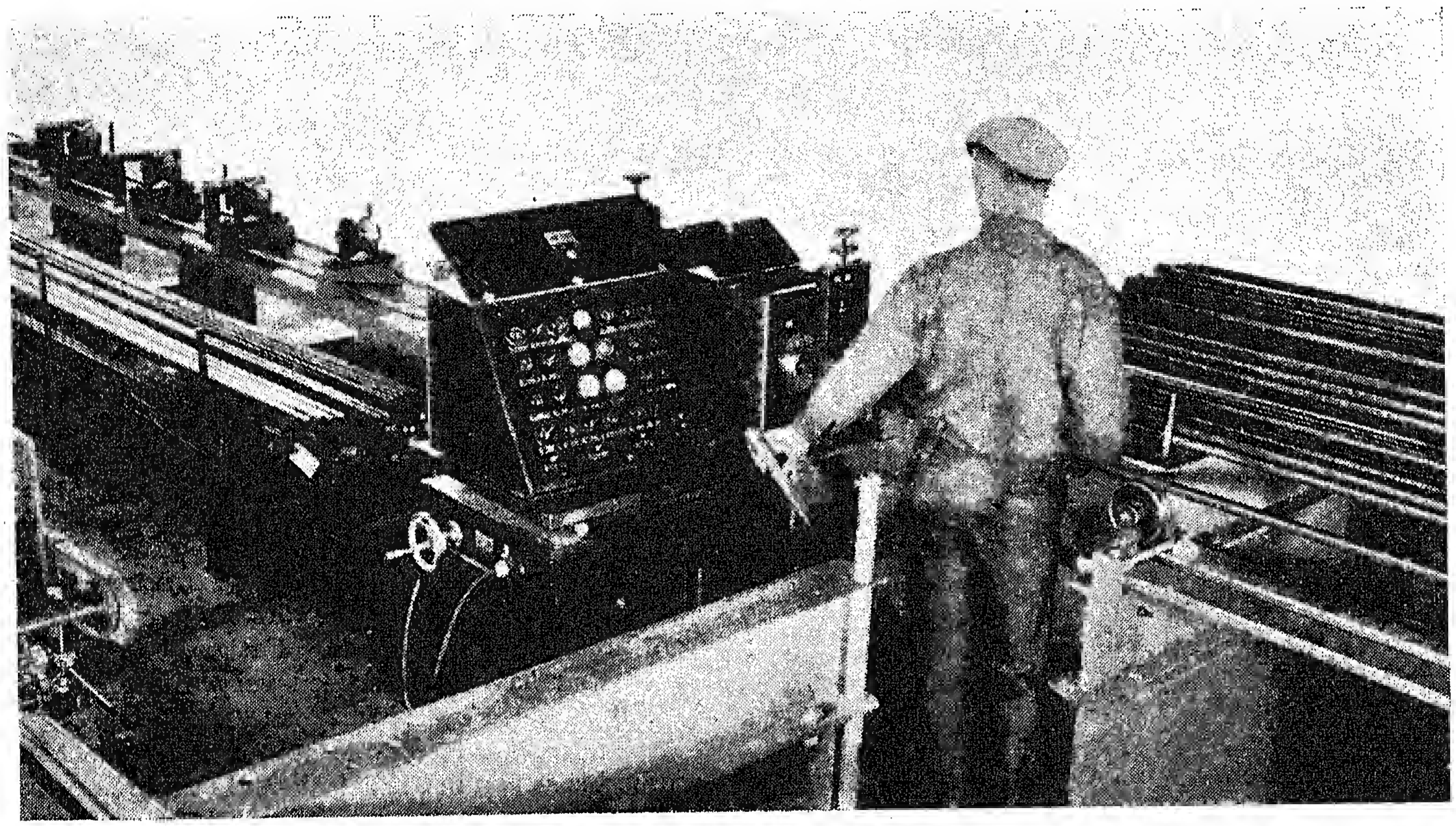


Fig. 3.—Testing bar stock by magnetic analysis (Magnetic Analysis Corporation).

By using current of high frequency, derived from a vacuum-tube oscillator, flaws in copper tubing are detected by the device shown in Fig. 4.

A somewhat different type of problem was solved by an apparatus by which the amount of magnetic inclusions in asbestos fibre used for insulating copper conductors is determined. The instrument is calibrated in terms of the percentage of iron in the form of $Fe_3O_4$ contained in a 10-g. specimen of the fibre. The apparatus can also be used for determining magnetic impurities in other insulating materials such as sand, mica, glass, etc.

Another form of apparatus, in which the presence of iron is made known by a visual or audible signal, is used for detecting the presence of iron objects in various non-metallic materials or baled scrap in which such iron would be objectionable.

A prominent manufacturer of razor blades employs a

* See Reference (18).

magnetic method for the continuous control of heat-treating operations. According to the patent,* the apparatus can be used to control either the hardening or tempering operation, or both. Strip steel is heat-treated by a continuous process in which the steel is fed in turn through an induction furnace, a quenching device, a magnetizing coil, another induction furnace, and another magnetizing coil. Within each of the magnetizing coils there is a search coil connected in series-opposition with a similar coil mounted within an auxiliary magnetizing coil. Suitable standards are located in the auxiliary coils, and photoelectric relays operated by the differential voltage induced in the search coils control the current in the furnaces.

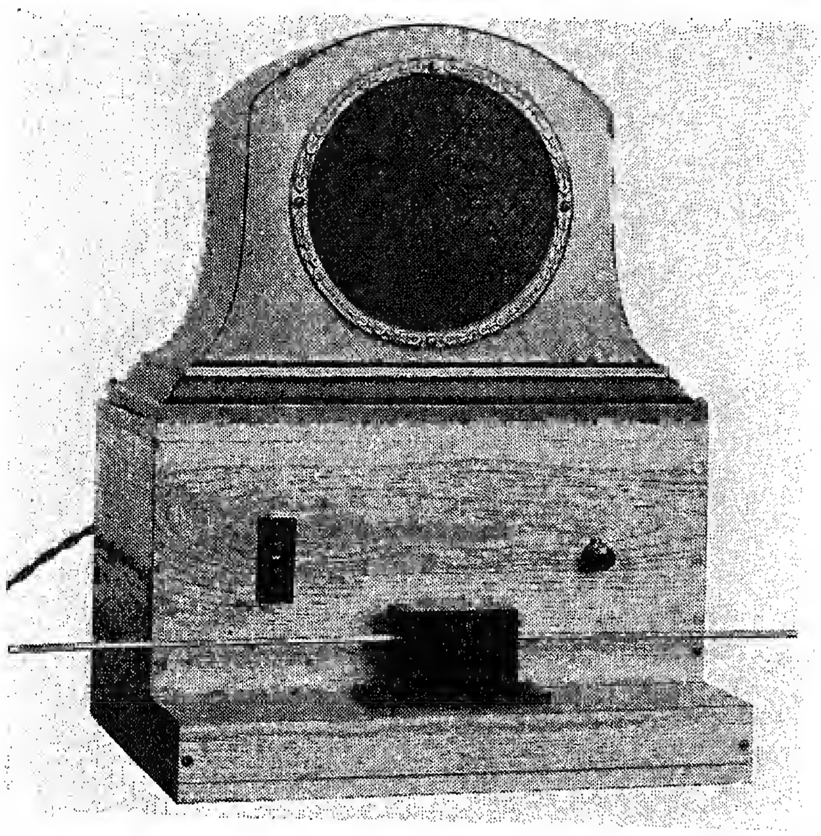


Fig. 4.—Electron tube device for detecting flaws in copper tubing (General Electric Co.).

One magnetic method of inspection† which has found wide application in the United States is generally known by the trade name "Magnaflux." This method was originally discovered by Hoke, and further developed and applied by de Forrest, McCune, and their associates. By this method, cracks, seams, and imperfect welds, are indicated on the surface of magnetized specimens by the adherence of finely-divided magnetic powder applied either dry or suspended in a suitable liquid.

The best method of magnetization depends upon the form and size of the piece to be inspected and the probable location of suspected defects. A common method is by means of a suitable electromagnet. Abnormal leakage from the surface of the specimen brought about by the presence of a defect produces magnetic poles to which the magnetic powder is attracted, thus outlining the defect. Best indications are obtained when the direction of magnetization is at right angles to that of the crack or other defect. Considerable ingenuity is often required in producing the right degree and direction of magnetization. The correct interpretation of the patterns also calls for the exercise of judgment based on experience. In some instances the use of an electromagnet for magnetizing the specimen is impracticable. Recourse is then had to direct magnetization either by means of conductors wrapped upon the piece or by sending current through the piece itself. This method is particularly suitable for detecting longitudinal defects in specimens such as rods or tubes.

* U.S. Patent No. 2041029, May 19, 1936.
† See Reference (19).

In one plant railway motor shafting made from heat-treated S.A.E. No. 3135 nickel-chromium steel bars is being tested by the Magnaflux method. It has been found that a d.c. arc-welding unit is a very convenient means for magnetizing bars up to $5\frac{1}{2}$ in. diameter, by passing current through the shaft from end to end for a period not over 10 sec. The residual magnetization has given an excellent indication of any longitudinal imperfections at or near the surface of the shafts.

The Magnaflux method has a wide use in this country. It is greatly relied upon in the inspection of parts of aviation engines and aircraft fittings.* Automobile parts, boiler tubes, tools, and other ferrous metal products, are being examined. More recently welded structures of many kinds have been examined.† Alloy-steel rotor forgings for steam turbines are examined for thermal cracks. Turbine blades or buckets have long been tested by this method. The "wet" method is used for the examination of forged and machined blades during manufacture, and the "dry dust" method has more recently been applied to the testing of blades in position in the turbine rotors and cylinders during routine inspection periods. Fatigue fractures in progress, that have always been very difficult to find, are readily revealed by this method.

An example of defects revealed by the Magnaflux method is shown in Fig. 5 (see Plate 13, facing page 572).

Magnetic methods are used not only for checking the quality of materials and parts but also for determining various quantities whose measurement would otherwise entail some damage to the material tested. For example, the measurement of the thickness of coatings of enamel, paint, nickel, tin, and the like on metal bases by mechanical or chemical means usually results in damage to the surface or even in some cases destruction of the piece itself. At least two commercially practical non-destructive methods are in use.

An electric enamel thickness gauge‡ is used to measure the thickness of enamel or paint on a flat steel surface. It consists of a gauge head and indicating unit and operates on a 110-V 60-cycle power supply. The reluctance of the magnetic circuit of the gauge head when placed on a coated steel surface varies with the thickness of the coating. This reluctance in turn affects the inductance of the coil in the gauge head, which is compared by a bridge arrangement with the inductance of a similar coil in whose magnetic circuit there is an adjustable gap. The indicator is a sensitive electrical instrument connected as the detector in the bridge circuit through a copper-oxide rectifier. By means of suitable thickness standards the indicator is calibrated to read thickness

* See Reference (20). † *Ibid.*, (21). ‡ *Ibid.*, 22).

directly in thousandths of an inch. The instrument is useful chiefly for measuring coatings at least several thousandths of an inch thick.

A somewhat different principle is utilized in a type of instrument recently developed at the National Bureau of Standards. The instrument is a portable spring balance arranged to measure the force required to detach a permanent magnet from the surface under test. One form of the instrument is designed to measure the thickness of nickel coatings on non-magnetic base metals* and the other, which employs a smaller magnet and a stiffer spring,† is used to measure the thickness of non-magnetic coatings on iron or steel. The force required to detach the magnet from a nickel coating increases with the thickness of the coating and is proportional to the thickness up to about 0·001 in. For non-magnetic coatings on a magnetic base the force decreases with the thickness. Both types of magnetic balance have been found sufficiently reliable for use under commercial conditions. They are particularly valuable for determining local variations in thickness of coating. The instrument with cover removed is shown in Fig. 6.

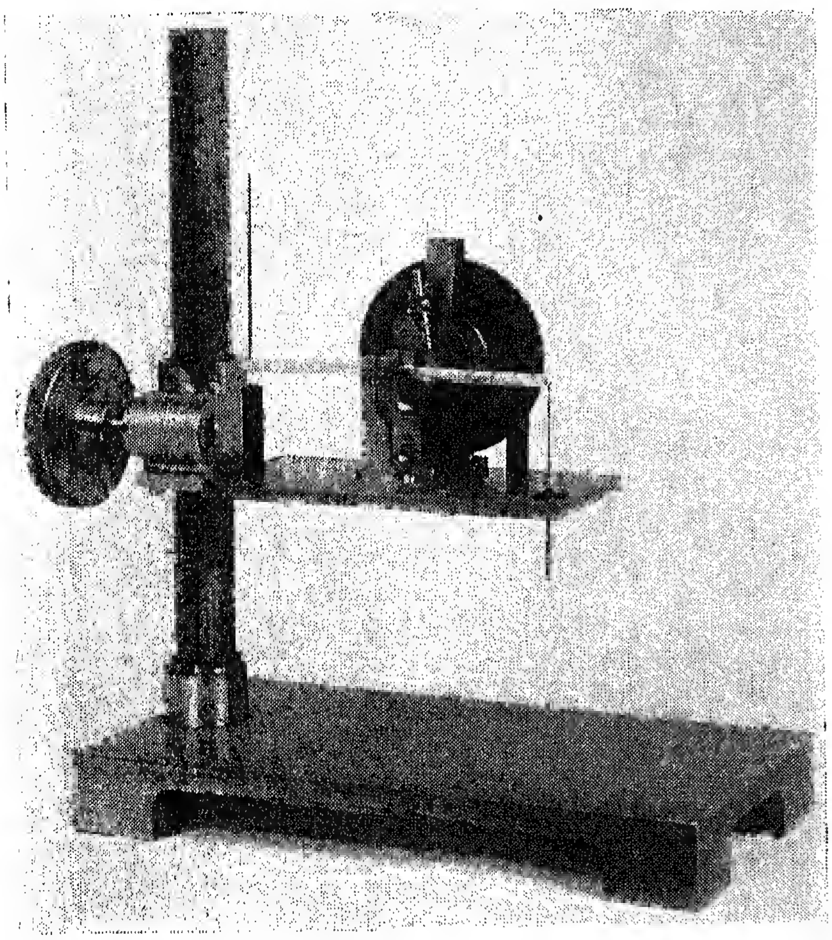


**Fig. 6.**—Magnetic balance for measuring thickness of coatings on metal (National Bureau of Standards).

Regarding the practice of testing the magnetic quality of electrical sheets, the standard method of testing electrical steels (core materials) is the Epstein test which requires shearing into small strips and consequently is destructive of material. Several steel manufacturers have recently developed a satisfactory method of testing complete sheets approximately 30 by 108 in. The chief objection to this test is that it tests for losses only, and with the flux flowing only in the direction of rolling, whereas in machines the flux flows in various directions relative to rolling. By making a number of tests on the sheet tester and then shearing these sheets and testing by the conventional method, it is possible to obtain a satisfactory correlation so far as losses are concerned. This test is being applied only to the poorer grades of material where the limits are not critical, and has not been applied as yet to the higher grade (lower loss) materials. Tests for other qualities such as permeability and ductility still entail destruction of sheets but require less material, and in addition are often waived except for periodic spot tests.

* See Reference (23). † *Ibid.*, (24).

### Electrical Methods

Electrical methods for non-destructive testing are not as numerous as those based upon magnetic properties. Perhaps the outstanding example of an electrical method is the one for detecting flaws in railway rails developed at the suggestion of the American Railway Engineering Association by the late E. A. Sperry.*

In its present form, the Sperry apparatus is built into a special self-propelled car, which moves over the track to be tested at a speed of 5 to 9 m.p.h. Mounted between the wheels of the rear truck are the main brushes which feed several thousand amperes, d.c., into the track. In order to obtain reliable indications, it has been found necessary to pre-energize the track by means of auxiliary brushes carried on the forward truck. The detector coils are mounted on the rear truck between the main brushes. Whenever a flaw in the rail causes a deviation in the direction of the current in the rail, a corresponding deviation in the direction of the magnetic field around the rail is produced. This induces in the detector coils currents which are amplified so as to operate relays carrying pens on a moving tape. At the same time, a paint gun ejects a spot of paint on the rail at the point of defect. The record table and tape are shown in Fig. 7 (see Plate 14).

When a flaw is thus located, the car is stopped and the extent of the flaw is determined by a drop-of-potential method using portable apparatus. From the result of this measurement it can be decided whether or not the defect is sufficiently serious to require the immediate removal of the rail. The defects commonly found are transverse fissures, compound fissures, horizontal split heads, and vertical split heads.

The practical value of this testing method is demonstrated by the fact that during the 7-year period 1931 to 1937 inclusive, more than 185 000 defective rails were discovered in approximately 355 000 miles of track inspected.

The Ronay† Arcronograph, the interior of which is shown in Fig. 8 (see Plate 14), is an apparatus which records variations in the voltage of the arc during the process of electric-arc welding. It has been found that the general quality of a weld and the location of defects such as voids, cold-shuts, and imperfect fusion, can be predicted from the graphic records obtained by this apparatus. The recording instrument is connected in the plate circuit of an electron tube whose grid potential depends upon the voltage across the arc. The characteristic of the tube is such that it is most sensitive in the

* See Reference (25). † *Ibid.*, (26).

upper part of the voltage range, which is the most important part. The instrument can be operated on either direct or alternating current and is used not only for checking the quality of important welds but also in connection with the training and rating of welders and for testing the quality of electrodes.

## PART 3—ACOUSTICAL AND GENERAL METHODS

There are many examples of non-destructive testing in use in the United States, other than the radiographic, magnetic, and electrical tests already discussed. No attempt can be made to offer anything like a complete list of such tests. In the space available, reference can only be made to several types or classes of tests to indicate the extent and general nature of such practices.

### Vision

It may appear somewhat unnecessary to include vision as a test measure in this presentation. With the development of some newer test practices, and especially the more general adoption of radiographic methods, there has been noted a tendency to forget that careful examination by eye, aided optically or otherwise, by experienced, trained personnel, is indispensable in all engineering activities. It should be remembered that many non-destructive test methods merely aid the eye.

In many plants one finds portable micrographic apparatus, often equipped with photographic means, for the examination of defects, questionable areas, and variations in structure in large forgings or castings from which even small specimens cannot be removed.

### Hardness Tests

Hardness testing is often considered as destructive testing, but actually it is widely applied as a non-destructive test for the control of heat-treating operations and to assure satisfactory physical characteristics in materials. Care must, of course, be exercised as to the size, location, and nature, of the impression or markings left by the test. The test may be made on surfaces having stock provided for machining, and the impression and all practical effects of it are thus removed. A boss, button, or other protuberance, may be provided on drop forgings, die castings, castings, etc., on which the test may be made, and the impression then removed or allowed to remain. Often the test is applied to the finished part and the impression or mark allowed to remain in the part. Unwise choice of test method has at times resulted in cracks—in hardened metal, for example—spreading from the impression. Improper location of the impression has at times resulted in fatigue failures in service. There are, however, many hardness-test methods available for practical use, and careful selection can be made for nearly any purpose.

One extreme example of such selection may be cited. The question of uniformity of hardness of journals and crank pins in finish-machined crankshafts for high-speed Diesel engines had arisen. It was desired to know definitely that pins and journals were of uniform hardness, around each pin and journal, and from one to the other along the shaft. The impressions left by many hardness testers were very objectionable, some quite dangerous. Moreover, it was very difficult to accommodate the shafts in the testing machines. The problem was solved by using the Herbert pendulum and swinging it as desired on the shaft pins and journals. The resulting shallow impressions were entirely acceptable on these surfaces.

### Proof Tests

There are a great many so-called proof tests in use to-day in this country. Some are looked upon as quite old-fashioned, but many are quite practical and valuable.

There is, for example, the proof testing of chain for all purposes, of eyebolts, of cables, and other gear and parts for lifting purposes. Usually a proof load is applied that is well above the rated service loads. In the case of welded wrought-iron chain the proof load is usually high enough actually to deform the links.

An impact proof test is used for carbon-steel and alloy-steel axles, shafts, and other forgings for locomotives and cars. Practice varies somewhat, but in general the forging is placed across supports and subjected to the fall of a tup of varying weight and from varying heights.*

The rules of the American Bureau of Shipping and Lloyd's Register of Shipping require that castings for hulls and anchors shall be subjected to a drop test on to a hard surface, and later that they be slung clear of the ground and well hammered all over with a heavy sledge hammer to test the soundness of the material.

Hardened parts such as knife-edges, bearing blocks, and buttons, are often loaded in compression beyond that to be encountered in service, to guard against internal cracks, high internal stresses, soft interiors, or other objectionable conditions. Such tests are usually supplementary to magnetic tests for surface cracks.

### Tests to Determine Cracks

Although the Magnaflux, or some other type of magnetic or electrical test, is being widely adopted for the determination of surface or near-surface cracks in ferrous materials, some of the older and perhaps cruder tests are still in limited use.

In one such method the material or part is covered with oil, which penetrates any cracks. Next the oil is carefully wiped from the surface, which is then coated with whiting. The part may be allowed to remain at rest, and in time oil retained in the cracks will produce discoloured streaks in the whiting. Or the part may be struck with sharp blows, or rotated slowly, to force retained oil out of the cracks and thus discolour the coating.

Large coiled springs are at times smooth steam-sand-blasted, and then immersed in kerosene for several hours, after which these are withdrawn and wiped clean of all surface oil. If cracks are present, in a short time oil which has penetrated into the cracks will seep out and show a darkened line on the " satin " finished surface.

So-called " buffalo " knives, for meat cutting, are tested by passing the blades between three rollers, which bend the blades a known amount. The amount of bending is so adjusted that a sound blade will come through the rolls and retain its shape, but should cracks be present actual breaking of the blade will always result.

* See Reference (27).

### Testing of Files

File makers make use of two tests that do no harm to satisfactory material but invariably ruin defective product.

In the so-called " ring " test the file is gripped by the tang, and struck sharply on its edge against a standard steel block. A good file rings true, but a cracked file will fall in pieces.

In the decarbonization test, a steel specimen having a Rockwell hardness, usually of 57–58 on the " C " scale, is drawn rapidly down over the teeth of the file. A standard file is unmarked, but a soft file develops a tell-tale marking.

### Testing of Hand-Saw Blades

One of the oldest reported non-destructive tests is still in use. Many years ago we received in this country from abroad a brief article that was reputed to be the oldest known account of heat-treating, the preparation, hardening, and proof testing of one of the old famed swords of the Near East. Two tests were required, the first as to its cutting ability, and the second that " the blade may be bent round about the body of a man and break not." It is still the practice to bend finished hand-saws until the two ends of the blade meet, without failure and without permanent set.

### Tests on Coiled Springs

The ordinary tension, compression, bending, and torsion tests on springs to determine their suitability and scale are in a sense non-destructive tests. In addition, springs are often tested to determine their freedom from any tendency toward taking a permanent set by compressing or stretching beyond their rated deflection, and even repeating this a number of times. At times, rapidly repeated compression tests have been made on springs for a greater number of reversals than they will actually get in service, to assure against objectionable permanent set and fatigue failures. As referred to elsewhere in this paper, the Magnaflux test, as well as the oil-immersion test, is applied to important springs.

### Tests on Turbine Rotor Forgings

Occasionally one finds a number of non-destructive tests applied to a single article. Large forgings for the rotors of steam turbines are a good example. In addition to the usual analyses and physical tests, which are sample tests, other non-destructive tests are in use.

Sulphur prints are made at the end surfaces to determine centre segregation, and to locate the " metallurgical axis " of the forging, which is considered quite important to some builders. Such prints are also made at end-faces and around the outside of the main body, especially at the largest diameters, to determine freedom from ingot corner segregation.

Magnetic tests, usually by the Magnaflux dry-dust method, are made over the " break-down " areas, that is, from the outside edge of the main body down and beyond the junction with the shaft portion. The test is also applied between stage discs, when they are integral with the shaft. The test is made to guard against fine thermal cracks or similar defects.

A smoothly finished hole is bored through the axis of the forging, and the walls of this hole are carefully examined with a borescope to determine complete freedom from injurious defects of any nature.

Then there is applied a stability test, to determine that the rotor will operate smoothly, without distortion and resulting vibration, when put in service. The rotor is put in a special lathe, and surrounded with a suitable heating furnace. Slowly revolving the rotor, it is gradually heated to 50 or 100 deg. F. above the expected operating temperature. Truth readings are taken at several, usually 5, selected locations along the length of the forging, during the heating, holding, and cooling periods. Tolerances of allowable distortions, and differences between final hot and final cold readings, are agreed upon.

Finally there are over-speed tests, both cold and hot, to approximately 20 per cent above normal operating speeds.

### Drilling Tests

Reference was made above to the inspection bore in rotor forgings. Such inspection bores are used in many other forgings. As a matter of fact, good practice rather dictates the use of such holes in all " large " forgings.

The rules of the American Bureau of Shipping require the drilling of holes in steel castings, at locations of questionable soundness, to determine freedom from defect. The practice is in general use in other fields as well, to explore known defects, to determine the presence of defects, to determine wall thickness, etc. The holes are subsequently plugged, and often the plugs are welded.

### Spark Testing

This rather old practice is still in active use in some places. An experienced operator touches a grinding wheel to the ends of all bars of steel in a shipment, before acceptance, and, observing the nature of the sparks, determines whether improper material is mixed into the shipment.

### Etching Tests

Some etching tests, other than the sulphur prints already referred to, are in use as non-destructive tests.

Spotting tests with various acids or other reagents having known reaction on materials are often used to separate parts or to weed out foreign material.

### Pressure Tests

There are a great many pressure tests that must rightly be looked upon as non-destructive tests. Some are purely to determine tightness and freedom from leakage. Others are for that purpose and in addition a sort of proof-testing of the material or structure itself.

In pressure tests, the pressure used is determined in different ways. In many cases it is some function of the expected operating pressure, such as $1\frac{1}{2}$ times the service pressure. In others the pressure is determined from a formula that will stress the material to some percentage of the yield point or tensile strength. In others it is purely an arbitrary pressure that is high enough to reveal leaks or burst faulty material and do no harm to normal material.

For high-temperature, high-pressure steam service, the older practice of hydraulic testing with water at room temperature is being supplemented with steam tests at operating pressures and temperatures. Steam-pressure boosters are now available for such testing.

Pressure tests vary in nature, depending of course upon the application at hand. Water, steam, and various oils, are used. Hot-oil tests are often used, with care being taken that proper oil of sufficiently high flash-point is used. Air is sometimes used with the part immersed in water, and soundness judged by air bubbles. Or soap suds may be placed on one side of a wall and air on the other, soap bubbles indicating leaks. Vessels to contain gases may be tested under pressure with that gas, and a chemical indicator used on the outside. Vacuum apparatus is tested under vacuum conditions.

Very often vessels, pipes, etc., are struck sharp blows with a hammer of specified weight, while subjected to the specified pressure tests.

### Hammering Tests

Reference has already been made to hammering tests on steel castings for ship hulls and anchors. Hammer tests are also made on pipe, on forgings, on welded construction, and on forge-welded construction. Repeated hammering tests are at times used to disclose high internal stresses in cylindrical parts, especially centrifugally cast cylinders.

### Stethoscope Tests

Kinzell and his associates* at the Union Carbide and Carbon Research Laboratories have made extensive use of the stethoscope in the examination of welded tanks, pipes, vessels, etc. It is claimed that the addition of the stethoscope to the older method of striking the part and listening with the unaided ear has made this a reliable test method.

### Testing of Porcelain and Glass

Non-destructive tests are applied in many cases to non-metallic materials. The testing of porcelain insulators and transmission-line fittings to make sure that they will perform under service conditions is one example. In one plant, all high-voltage porcelain parts designed for service above 6·6 kV are given a so-called routine flash-over test. This test consists of setting the porcelain parts on a flat metal surface, the other terminal usually being set into the inside. In most of the routine tests the insulators are run over a moving conveyor, which facilitates handling large quantities. The test is made with a 60-cycle voltage, and the flashover is continuous for a period of 3 to 5 min. The continuous flashover is obtained by using a transformer with resistance in the primary, so that, as soon as the arc forms, the voltage decreases and the arc goes out.

In addition to the flashover test, routine mechanical tests are made on all suspension insulators after assembly with metal parts. Usually they are tested to about 40 per cent of the guaranteed strength. Some are tested in cantilever or torsion, or compression. Most of these approach the expected maximum service conditions as regards loading, although some compression tests are at double the load expected in service.

* See Reference (28).

Various glass articles are being tested for internal stresses, by means of polarized light. The Polaroid Corporation has recently developed a glass strain detector, meeting the specifications of the testing committee of the Glass Container Association. It is built for routine inspection of items in production.

## CONCLUSIONS

The value of non-destructive testing methods has been definitely established in industry. This has stimulated the growing interest referred to earlier. The discussion of which this paper becomes a part will awaken further interest; it will permit comparisons of methods and results in various parts of the world; ideas will be born that will grow to new methods and further applications. Naturally, there are many methods already in the course of development. The studies by Kinsley* and Canfield† have already been published and show a trend of thought. Several investigations dealing with the detection of cracks in non-magnetic materials show much promise. Newer magnetic methods are nearing completion.

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* See Reference (29). † *Ibid.*, (30.)

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[The discussion on this paper will be found on page 580.]

# DISCUSSION ON THE PAPERS (SEE PAGES 519–579) PRESENTED AT THE MEETING ARRANGED BY THE JOINT COMMITTEE ON MATERIALS AND THEIR TESTING, 25th NOVEMBER, 1938

**Prof. W. M. Thornton:** The discussion, I take it, may have two directions: one may give one's own experience of the methods described in the paper, or one may describe new methods that are not as yet in common use. The term "non-destructive" is in general applied to tests made on materials or structures before they are put into service; but there is an equally important application to old structures which may have become weakened by corrosion or erosion. In these cases, such as boiler tubes or shells, it has been difficult, and in many cases impossible, to measure the extent of the corrosion without removing—in effect destroying—a tube or drilling a hole in a plate through which a gauge may be inserted. This would also come into the category of destructive tests, in that until the hole is plugged the boiler is out of action. I propose to describe a new method of finding the thickness of steel or iron plates or tubes by measurements made from one side only of the metal. It consists in passing a direct current between two points on the surface of the plate and measuring the potential difference between two other points near the line of the current flow. Usually these points are placed between the current contacts, but they may be beyond them or even at right angles to the line joining them. The method is being described fully elsewhere,* but it may be said that thicknesses of steel plates up to $1\frac{1}{4}$ inches may be quickly measured with an accuracy of about 2·5 %, and that by an extension of the method it is possible to measure with the same order of accuracy the thickness of steel forgings or iron castings up to 3 inches. It has been found useful in measuring the thickness of boiler and superheater tubes. It is a comparative and not an absolute method, but it is in general possible to make check tests on similar materials of known thickness, though this is not essential when measurements at two related spacings can be made. For rapidity of testing, the current through the plate is adjusted by a rheostat until the potential difference reaches always the same value, though for some purposes it is convenient to work with a constant current and to measure the potential difference. [Prof. Thornton then showed a number of slides giving the results obtained on plates and tubes.] An average difference between measurements made on tubes by a micrometer and by the electrical method was 0·001 inch; and in another case of superheater tubes 0·002 inch. The range of thicknesses so far measured by this method is from 3 inches to 0·025-inch steel. The apparatus is portable and has found an application in shipyards, chemical works, and boiler plants. It has also been used to measure the thickness of cylinder walls to estimate the core shift. As a method of non-destructive testing it enables measurements of thickness to be made from one metal surface which have hitherto not been possible by any method.

**Dr. E. H. Rayner:** There is one type of non-destructive testing which is probably not very well known, and that is the testing of insulating materials under high voltages. The ordinary test of insulating material under high voltages is a test to destruction, and by carrying it out one can learn a certain amount, but it is a brutal test. Unless one obtains some further information on the way to destruction, the test gives but little information. It is somewhat similar to the testing of mechanical test-pieces without an extensometer and other such apparatus.

For the testing of insulating materials, not to destruction but close to it, a method was developed a good many years ago, based on measuring the energy absorbed in them. With organic materials generally the energy loss, resulting in rise of temperature, increases with temperature; and the effect may become cumulative, producing a continuous rise in temperature and in the power dissipated, until disruptive failure occurs. The failure may be predicted with certainty an hour or more before it occurs; and if the voltage supply is cut off a few minutes before failure would take place, the material may not be permanently altered, and the same history may be repeated several times in succession. A number of cases of this kind are given in a paper on "High-Voltage Tests and Energy Losses in Insulating Materials."*

Prof. D. R. Hartree has recently obtained theoretical curves of the same type,† produced mechanically by the Bush differential analyser at Manchester University. The machine has to be supplied with some relation between temperature and power loss, and the empirical function assumed is shown to be not far from the truth by the agreement between the experimental electrical results and the graphs produced mechanically by the machine.

Another type of non-destructive testing, providing quantitative information on temporary depreciation of functional capability, is the measurement of the current or power taken by high-voltage insulator systems under adverse conditions, especially frost and fog combined. The results show that there may be little or no margin between working voltage and flashover, when such conditions are long continued, particularly when the line is not kept alive. When a line is kept alive, the power involved in the conductance of fog deposit may provide sufficient heat and evaporation to render the conditions safe. If a "dead" line is excited to the working voltage under similar conditions, flashover may result at once. Information on this subject has already appeared in the *Journal*.‡

**Mr. A. G. Warren:** I should like to refer briefly to Prof. Thornton's description of his apparatus for measuring the thickness of metal plates. It happens that I have written a paper§ describing a somewhat similar method, which does not, however, require a knowledge of the properties of the plate. Many methods have been devised which have deduced the thickness of a plate on the assumption that one knew either its electrical conductivity or its magnetic permeability. I have, however,

* B. M. Thornton and W. M. Thornton: *Proceedings of The Institution of Mechanical Engineers*, 1939, vol. 140.

* E. H. Rayner: *Journal I.E.E.*, 1912, vol. 49, p. 3.

† Not yet published, but soon may be.

‡ W. G. Standring: "Some Measurements on Characteristics of Insulator Strings," *Journal I.E.E.*, 1934, vol. 75, p. 111.

§ "Measurement of the Thickness of Metal Plates from One Side," *Journal I.E.E.*, 1938, vol. 84, p. 91.

*Plate 15*

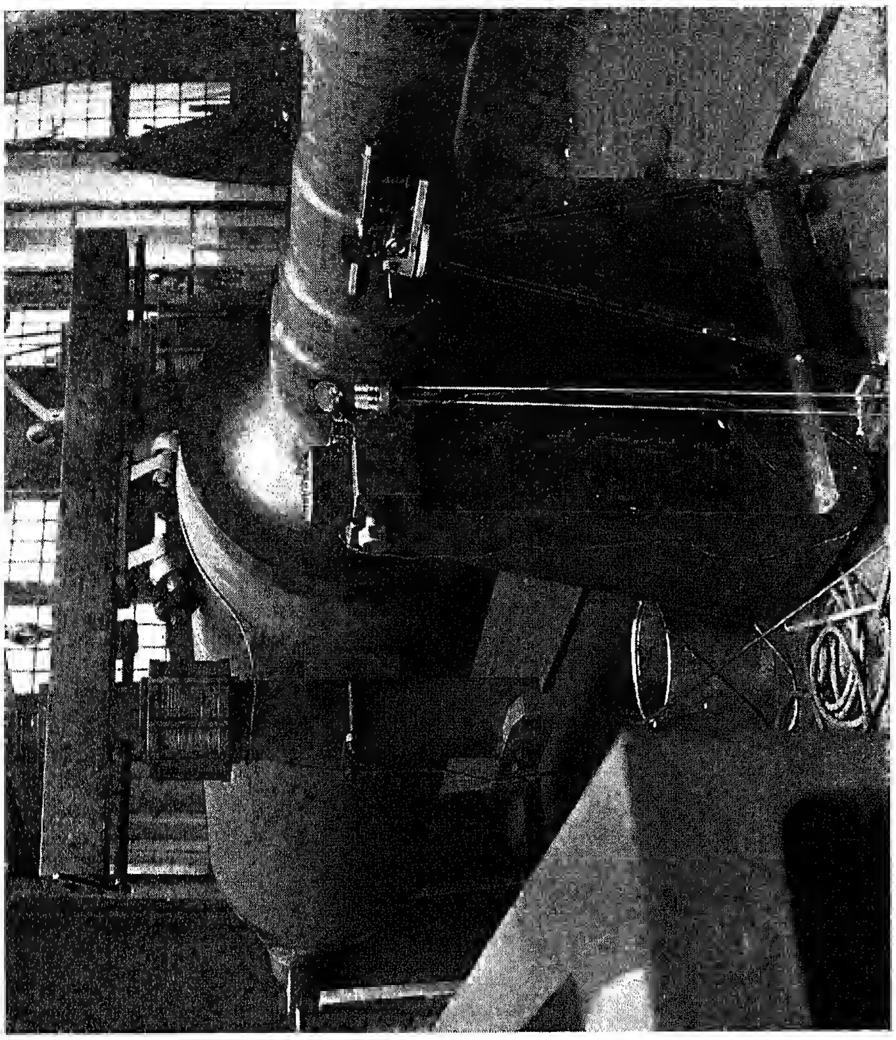

Fig. B

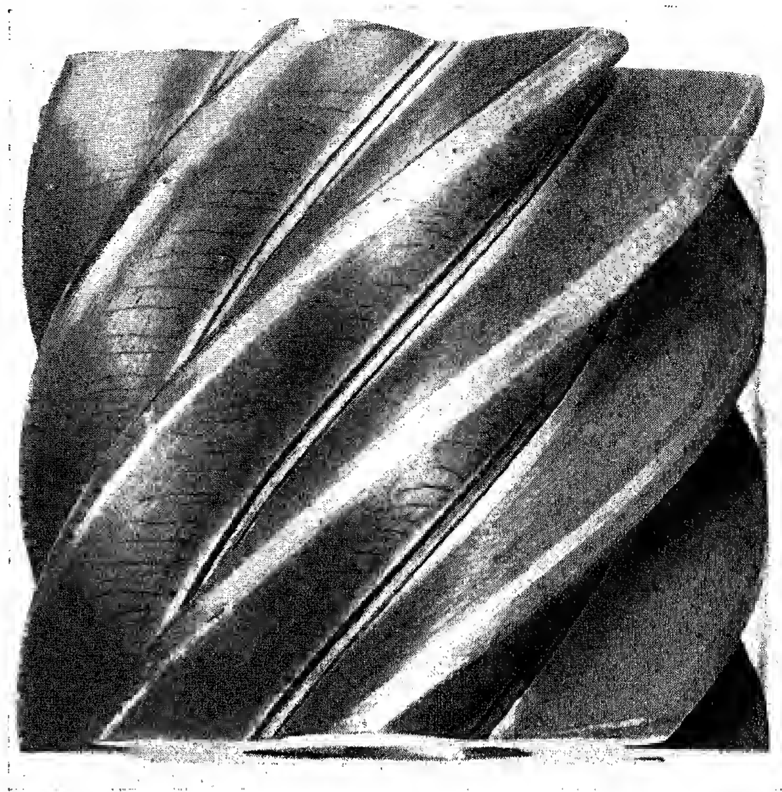

**Fig. D.**—Case-hardened worm, showing transverse type of grinding cracks revealed by magnetic test.

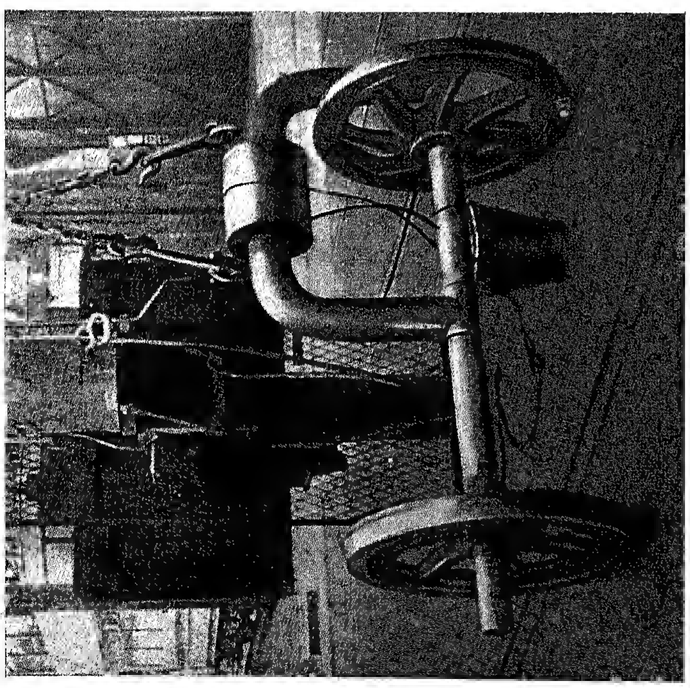

Fig. A

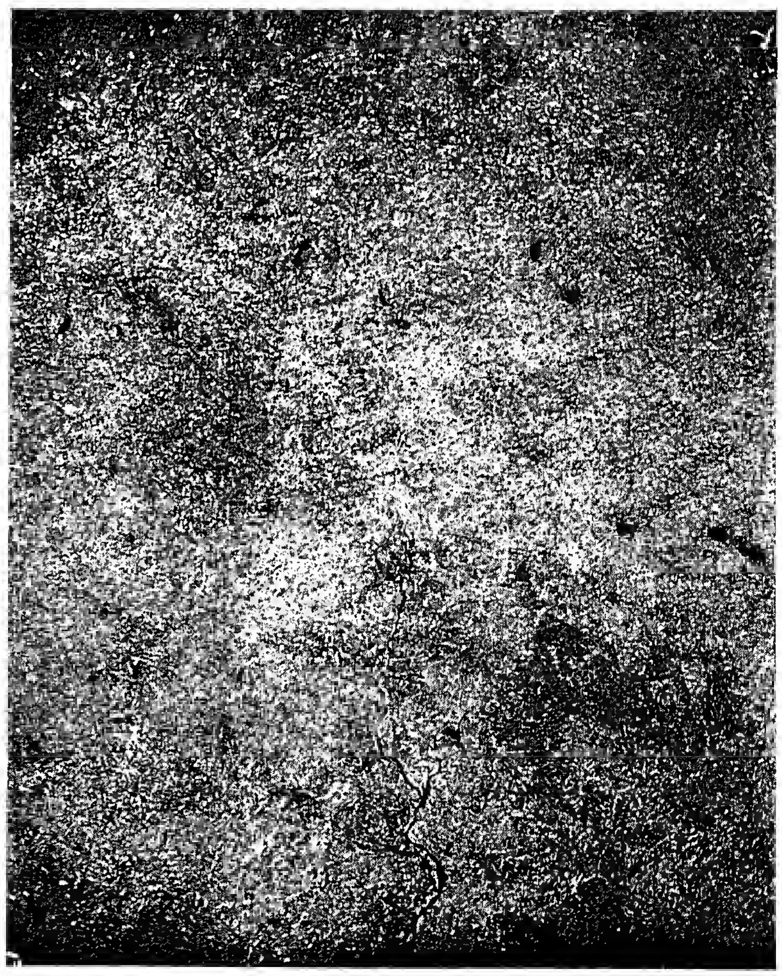

Fig. C



(*Facing page* 580.)

*Plate 16*

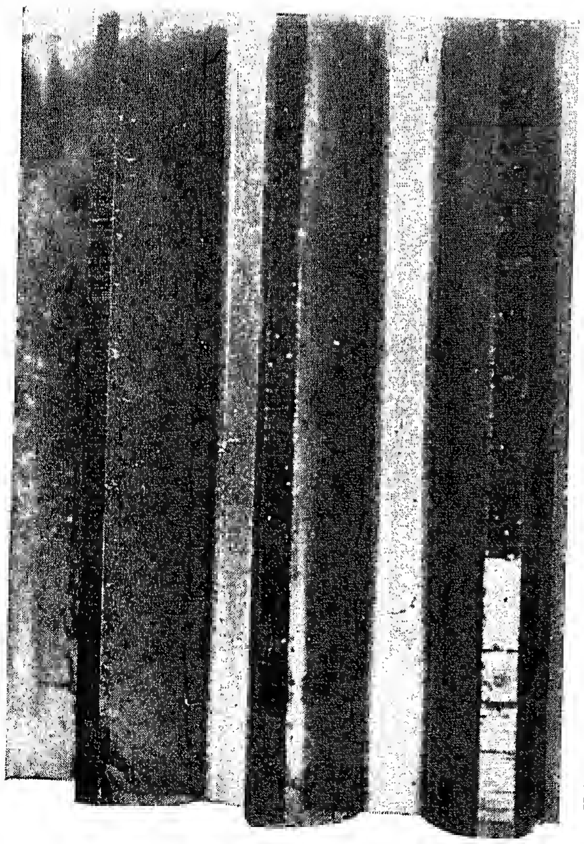

**Fig. E.**—Case-hardened pinion, showing longitudinal type of grinding cracks revealed by magnetic test.

**Fig. F.**—Section through grinding crack normal to surface of steel. (Magnification 50 diameters.)

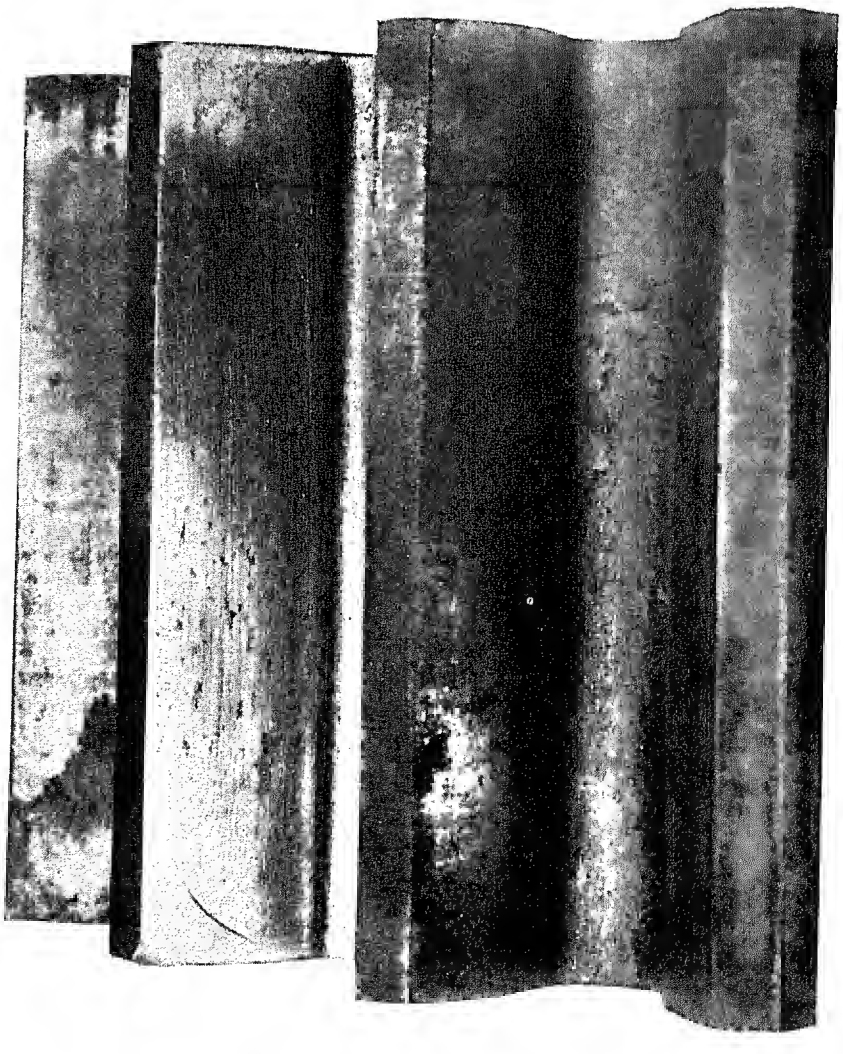

**Fig. G.**—Quenched pinion after magnetic test, showing hardening crack near end of tooth.

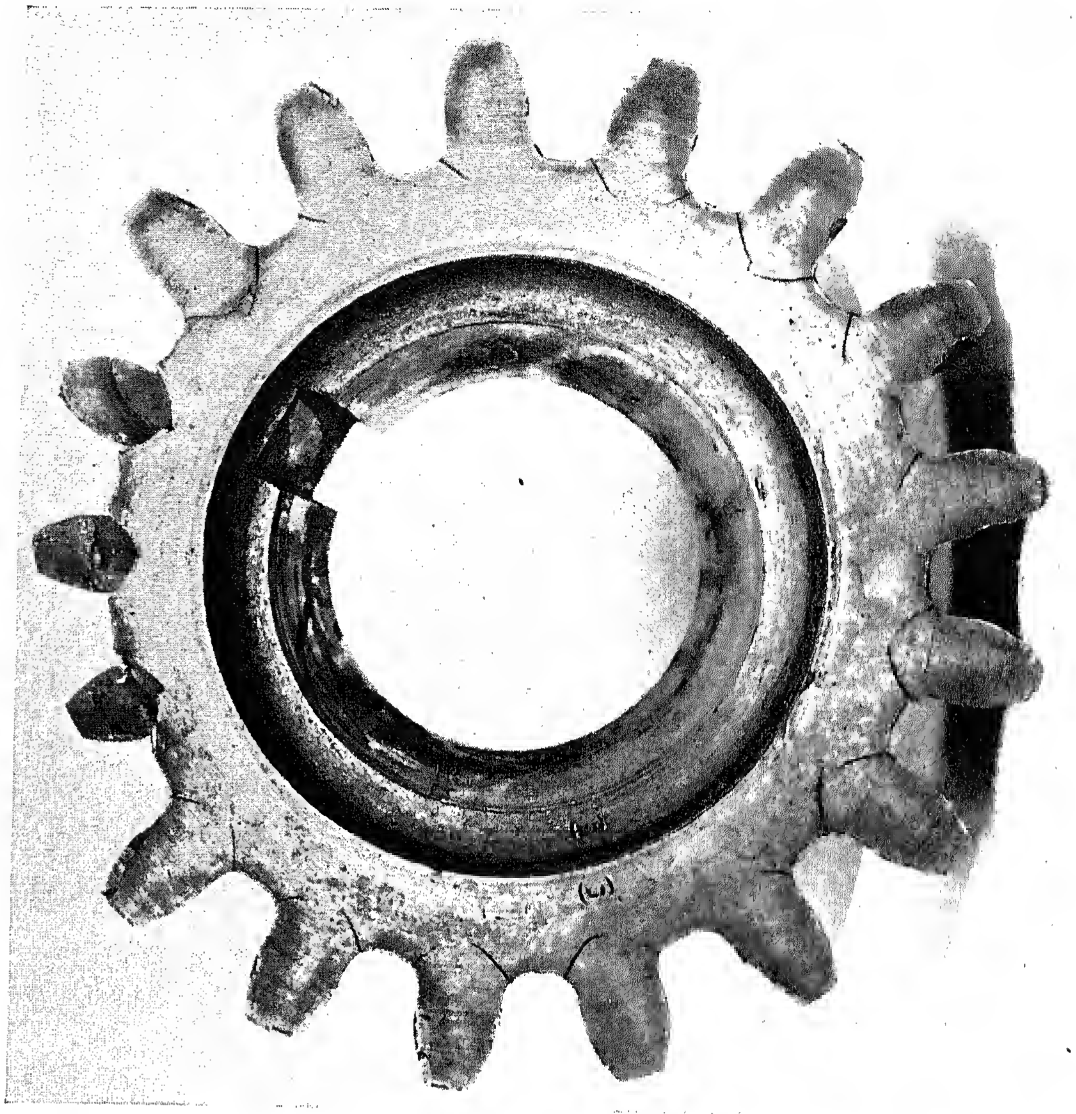

**Fig. H.**—Fatigue cracks on ends of traction pinion revealed by magnetic test.

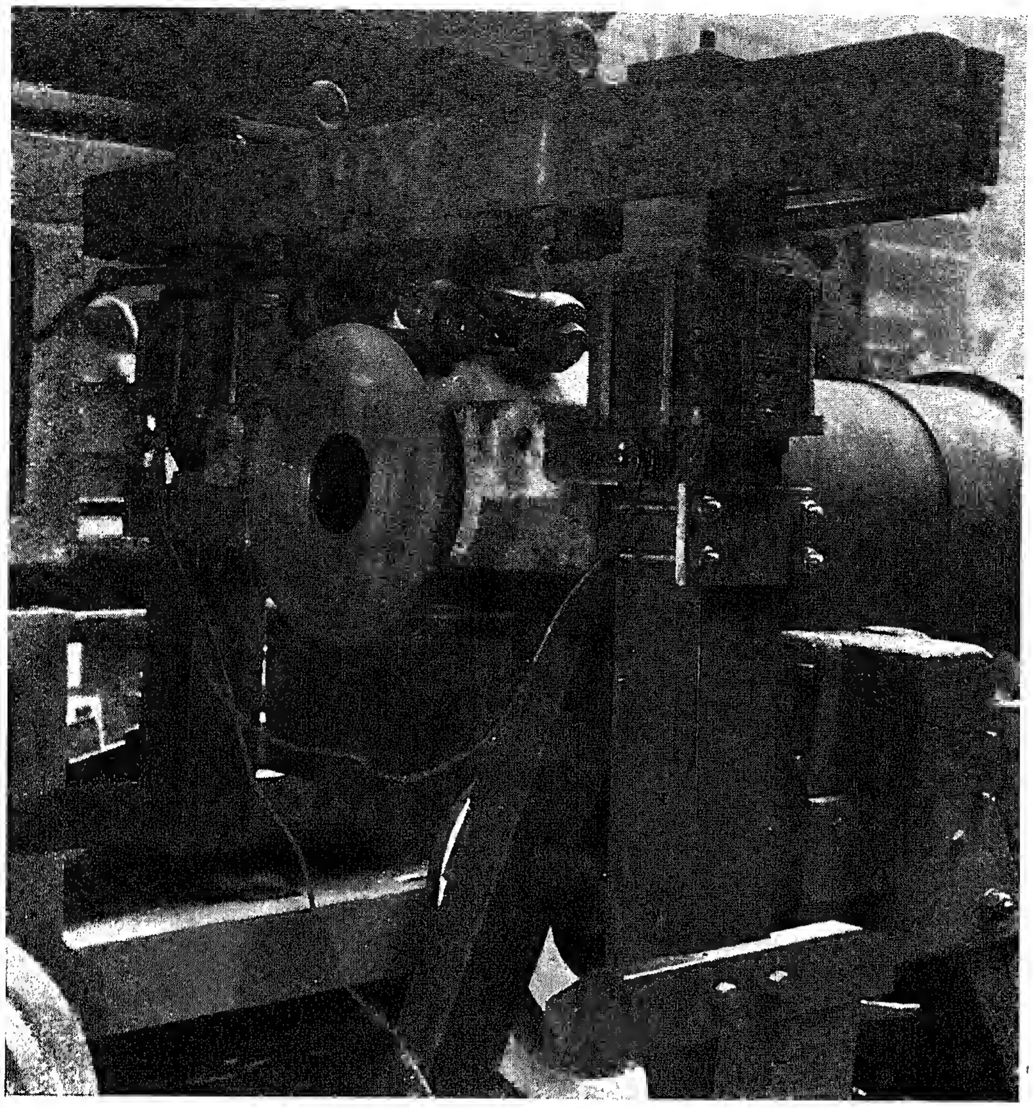

**Fig. J.**—Shaft undergoing magnetic test.

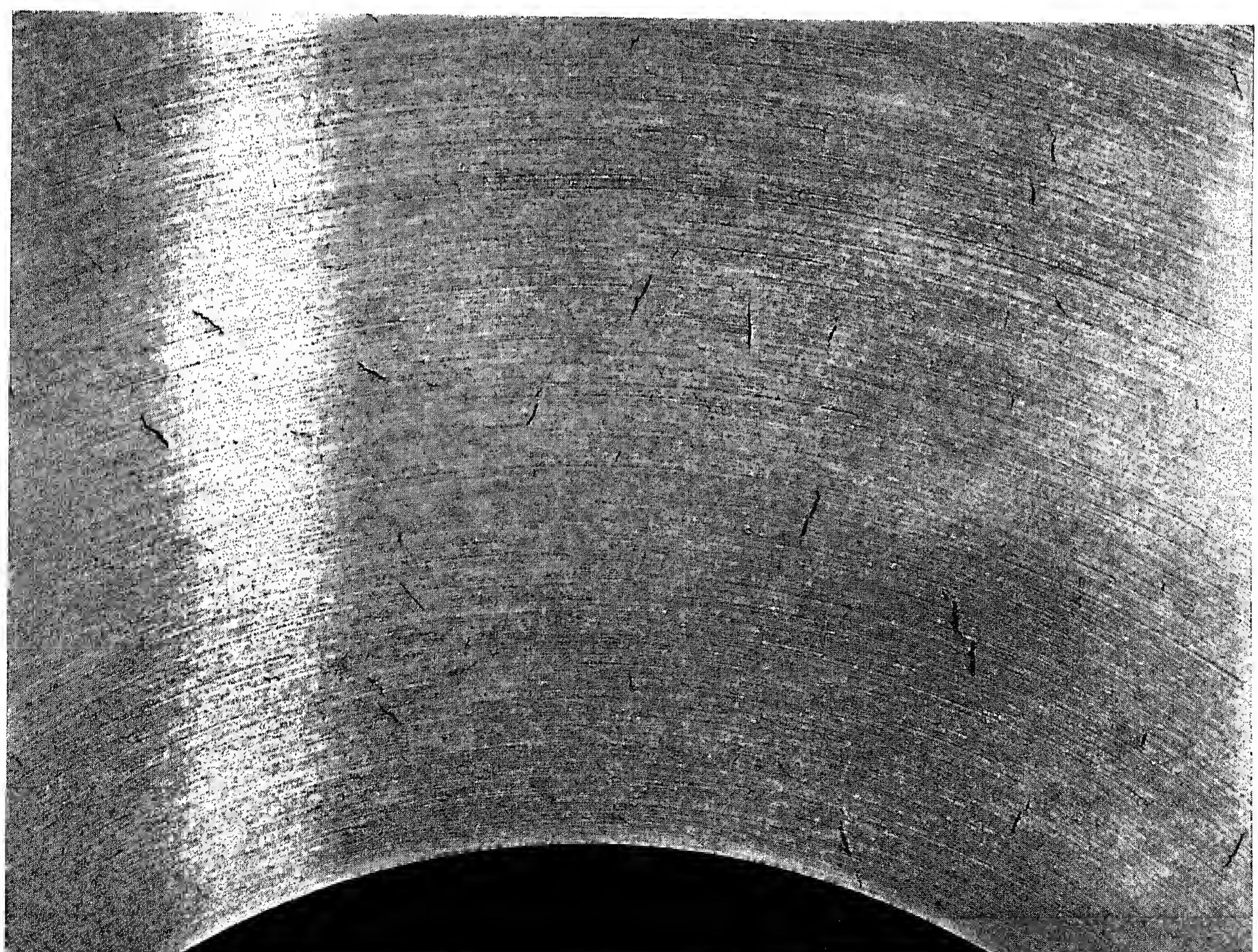

**Fig. K.**—Hair cracks on end surface of bored shaft seen in Fig. J. (Three-quarters natural size.)

come across steels of the same composition which have varied in permeability and conductivity in the ratio 3 to 1. I therefore aimed at inventing a method which would be purely geometrical. Instead of contacts in a line, four contacts were employed forming the sides of a square. Between two adjacent contacts a standard current of about 4 amperes was passed, and the difference of potential was measured between the other two contacts. If such a square is placed on a plate which is thin compared with the dimensions of the square, the same reading is obtained for the same current whatever the size of the square; but if it is placed on a plate which is thick compared with the dimensions of the square, then if one halves the size of the square the reading is doubled. When the size of the square is of the same order as the thickness of the plate, there is a rapid change in the voltage measurement which is obtained for a given current as the size of the square is reduced.

A curve can be drawn which applies equally whether the metal to be tested is, for example, aluminium or iron. If there is a difference of from 20 % to 70 % between readings taken (*a*) with one size of square and (*b*) with a square of half the size, those readings are acceptable; and from a curve is read off a ratio by which the size of the smallest square must be multiplied. For instance, if we use a square of $\frac{1}{2}$ in. and obtain a certain reading, and then a square of $\frac{1}{4}$ in. and obtain $1 \cdot 4$ times the reading, against $1 \cdot 4$ we find the figure $1 \cdot 6$, and that means that the $\frac{1}{4}$ in. must be multiplied by $1 \cdot 6$, giving $0 \cdot 4$ in. as the thickness of the plate. The errors obtained on steel plates are of the order of 3 %, as indeed they should be, because the surface conductivity of a rolled plate is greater than the conductivity of the material within.

The remaining remarks which I have to make are chiefly concerned with the Magnaflux or ferrographic method, and will deal with the examination of fairly large numbers—not thousands but dozens—at a time of castings and forgings, which may vary in weight from a few hundredweights to several tons. Such objects cannot conveniently be put into one of the machines described in the first paper, and the inspector has to take the testing apparatus to the forging instead of having the forging brought to him. The apparatus has to be effective, portable, and adaptable. The method of flash magnetization supplies the solution to a very large number of the problems which occur in practice. The method is rapid and the apparatus is cheap and portable; it can be put into an attaché case. Flash-magnetization methods require, of course, a closed magnetic circuit. This condition is satisfied in many cases such as turbo rotors, boiler drums, and spur wheels. With a little ingenuity one can make almost any object into a closed circuit—even a piece of flat boiler-plate.

I disagree with the remark on page 526: "It is advantageous to utilize the applied field rather than the remanent field, since with soft materials the latter may be inadequate." The remanence of most soft materials is greater than that of most hard materials: the coercive force is less, and as a result of experience I believe in using the remanent magnetism rather than any applied field. It is difficult to be certain of the value one employs in an applied field, and so easy to get too big a field giving results which are very misleading.

One small difficulty which crops up in connection with Magnaflux methods is the magnetostrictive pressure mark, particularly in nickel steels and nickel-chrome-molybdenum steels. In most cases it is obviously a pressure mark, but in some cases it very closely resembles a roke. German engineers have been mystified by it in dealing with springs; they have obtained marks down the spring which might be interpreted as cracks but which in fact are not cracks. They can be removed by demagnetization in the sense in which Ewing used it when dealing with magnetostriction. There is a brief note on the subject in one of the References at the end of the paper by Dr. Fleming and Mr. Churcher.*

Dr. Berthold also refers to the same method of inspection and deals with the case of a crevasse below the surface. Such a fault can be detected comparatively easily. For instance, a hole $0 \cdot 1$ in. diameter, $0 \cdot 5$ in. below the surface, can be located by long-flash methods and shown up well by the magnetic spray. It would, however, be more valuable to be able to detect a blow-hole $0 \cdot 1$ in. diameter which is below the original surface and will be apparent on the machined surface.

The electrodynamic methods of inspection mentioned by Dr. Berthold do not seem to have been used very extensively, although in the case of machined material they have a very wide field. They are generally based either on the rope type of machine or on the disc type of machine. By the rope type of machine I mean an arrangement through which the material is passed continuously, while one examines a whole section at a time for discontinuities or abnormalities. Such machines are nearly all based on the work done by Wall† in this country some years ago. The disc type of machine is one in which the unit such as a turbo disc or gun tube is rotated and one searches for flaws. Most apparatus of this sort is based on work done by Burrows and his collaborators many years ago in the U.S.A. Some of the modern disc machines are but very poor imitations of the apparatus used by Burrows, and one can only guess that many of the present-day workers in this field are ignorant of his work.

Dr. Berthold mentions the difficulty met with in such measurements on account of variation of the permeability of the material under inspection. That variation of permeability can be turned to good account. It is possible so to adjust the detecting apparatus that it is comparatively insensitive to variations of permeability, and when this has been done the indications of the output instrument are usually due to flaws. On the other hand, the apparatus can be so set that it is comparatively insensitive to variations of surface conductivity but sensitive to variations of permeability. The usual cause of variation of permeability, in a hard steel at any rate, is internal stress; thus, in the case of a heat-treated material, the same apparatus may be used both for detecting flaws and for detecting imperfect equalization of stress after heat treatment.

**Prof. W. A. Wales:** I notice that the papers omit to mention American practice in regard to insulation testing. During the last 15 years engineers in the United States have been developing the Doble testing set, which

* Supplement to *Engineer*, June, 1938.
† *Journal I.E.E.*, 1929, vol. 67, p. 899.

employs a voltmeter, a microammeter of the rectifier type having a range from $20\,\mu$A up to 9 mA, and a moving-needle wattmeter with ranges of 0·05 watt to 1·2 watts and 1 watt to 12 watts. The development of the wattmeter has been a considerable achievement. This method of testing is also being used in this country.

American engineers have also evolved a standard form of test which enables the dielectric loss of oil to be measured. The accuracy of the above set is about 6 % compared with that of the Schering bridge. One could, of course, standardize the method directly with reference to the Schering bridge, but there is an error in use due to the phasing angle in the wattmeter itself.

With regard to the contacting device for high-resistance measurement, I should think that metal spraying would solve many of the difficulties which are experienced in obtaining effective surface contact.

Finally, I would mention that the valve wattmeter for dielectric measurements has almost the same sensitivity as the wattmeter developed by Doble. If we paid more attention to the use of wattmeters in this country, we should obtain our results more quickly and be able to give them much wider application in routine tests.

**Dr. R. W. Bailey:** The magnetic method of testing described by Dr. Fleming and Mr. Churcher originated in England, quite independently of its earlier development by Hoke in America, and was devised by the company with which Dr. Fleming is associated. It may be of interest to mention how it arose in England. About 1922 or 1923 a piece of magnetized nickel-chromium steel was being polished for metallurgical purposes when it was noticed that the exceedingly fine debris from the polishing lined up along a sharp curve, and did so repeatedly. It was evident that there must be some discontinuity to account for the effect. On the polished surface nothing could be seen, but further examination revealed an exceedingly fine crack. Thus was disclosed a very sensitive method of crack detection which required (i) magnetization and (ii) an extremely fine iron powder. The investigator succeeded in creating a process for the manufacture of the extremely fine iron powder. The method was tried out and proved to be satisfactory.

At about the same time, in 1923, stainless-steel turbine blades came into extensive use. A blade broke in the course of manufacture, although previously there had been no visible crack. Examination showed, however, that a crack of such fineness as to be invisible in the ordinary way had existed. How to detect this type of defect in stainless-steel turbine blades was a serious problem. The iron-dust method was applied in the way in which it had been discovered, i.e. we used dry dust and had a number of blades magnetized and suspended in a chamber where they were exposed to the dust. The experiments produced an objectionable "fog" of iron dust in the laboratory, and the dry method was abandoned. The investigator then put the dust into paraffin, and its application to the blades was immediately successful.

About 1925 an engineer of the L.C.C. Tramways was at the works and saw the method being applied to the routine testing of hardened and ground gears. He asked whether it would detect cracks in axles, and to determine the point we designed an arrangement for axle-testing (Fig. A, see Plate 15, facing page 580) which proved the effectiveness of the method. Shortly afterwards we applied the method to the examination of the bores of rotor forgings (Fig. B, Plate 15).

Not until later on, I believe, was the method used to any extent in the United States, although Hoke had taken out a patent in the U.S.A. prior to our own original work on the subject. Six or seven years ago when in the U.S.A. I inquired of a large firm whether they used the method, and was told that it had been tried but not with satisfactory results. I examined a sample of the iron powder they were using and found that it was not fine enough for the purpose.

There are one or two points to which I should like to refer which are dealt with in the papers. Dr. Berthold's explanation of this magnetic method leaves out of consideration the following factor which in practice may be quite important. In applying the iron-powder method of testing, iron powder catches iron powder, and consequently it is important to arrange for a gentle flow of the liquid over the surface, so that the very fine iron particles drawn to the defect can assist in collecting other particles.

Dr. Berthold makes the statement on page 530 that negligible flaws are exaggerated by the use of thin oil. The dangerous character of a crack, however, does not depend on its width, and therefore one must resort to methods which can exaggerate very fine cracks in order to discover them. To detect very fine cracks, e.g. 0·0001 in. wide, we find it essential to use thinner media than oil; methylated spirits is used in some cases.

There are, of course, limitations to the iron-powder method, and the most serious is that it only detects defects at or near the surface. At present there is no reliable method of non-destructive testing for revealing internal fissures of the order of 0·0001 or 0·001 in. thick. X-rays have proved a great disappointment for the reason that, as a rule, cracks and fissures are really irregular, as shown by Fig. C (Plate 15).

The non-destructive testing of forgings is comparatively straightforward because the defects which may be encountered are usually of known type and location. Two principles, however, must sometimes be employed. One is to arrange the forging, and if necessary the heat treatment, so that if defects are produced they occur where they can be found with certainty. This may sometimes involve making a forging of a different shape or dimensions from what would otherwise be required for the part. The other principle is that one is sometimes justified in changing the dimensions or form of the part, although it may make the heat treatment more severe and thus be more likely to produce defects, in order that the defects may be located outside the forging as finally machined.

In the case of castings, we are in a difficulty. We cannot find certain kinds of defects such as very fine fissures because they are beyond the range of X-rays, and assurance can only be given where cracks are fairly substantial or where there is porosity. In many cases, therefore, a guarantee of entire freedom from defect cannot be given, and where it is needed forgings must be employed.

**Dr. F. Förster:** So far as magnetic testing is concerned, there are certain limitations to the powder method which make it difficult to find flaws in steel

pipes and vessels by this means. I make use of a method employing direct current combined with alternating current, and a search coil for investigation of the magnetic field. By the direct current I eliminate the inhomogeneity of permeability of the material, and by means of the alternating current I explore the field with the search coil. It is necessary in some cases to develop a special form of coil, so that the sensitivity may be as high as possible. With this method it is possible to detect not only cracks which run perpendicular to the surface, coming out at the surface, but also cracks which are parallel to the surface. It is also possible to detect blowholes by this method in cases where the powder method would not show any flaw.

**Mr. L. E. Benson:** I should like to refer briefly to the interpretation of the results to be obtained from the powder method of crack detection, because in the absence of special experience it is frequently much easier to carry out the technique of the test than it is to know what to do with the results which are obtained. The firm with which I am associated has probably done more to develop this test and its applications than any other concern, and our experience is that the method is capable of yielding a good deal more information than is often realized. In some cases the information to be derived from it could not be obtained by any other method. There are, however, two conditions which should be observed.

It is necessary in many cases that the test should be applied in conjunction with other non-destructive tests—sulphur printing, hardness tests, micro-examination, and so on. It is also necessary that the magnetic tests should be applied with a knowledge of the metallurgical history of the part. The most important features are the relation of the forging, for example, to the ingot from which it was made, and also the history of the forging, particularly as regards periods in its manufacture when thermal stresses would be likely to develop, e.g. during heat treatment.

Taken in conjunction with this information, magnetic tests at the surface can give great assistance to the engineer. The case of the internal soundness of rotor forgings, mentioned by Dr. Bailey, is an outstanding example, and I would also mention the testing of rotor bores and trepanned cores.

Incidentally, the procedure referred to in the paper by Messrs. Lester, Sanford, and Mochel, for testing turbine rotors by a combination of different testing methods, was originated, I believe, in this country.

It may be impossible to tell from the results of magnetic testing alone whether defects so found are sufficiently dangerous to justify immediate rejection, or whether they are of a less-dangerous character, e.g. associated with local unsoundness along the axis of the original ingot. It is, however, quite possible to take sulphur prints in the bore of a rotor, and the results of these and other tests may make a confident decision possible; such results may even enable an apparently defective forging, as shown by the magnetic test only, to be used with every confidence after the local defects have been dealt with in a suitable way.

The types of defect generally encountered fall into recognizable classes, and it is important that the type of defect encountered should be recognized quickly, because it may be necessary to reject not only one part but all the parts made from that ingot, or even, in an extreme case, all the parts made from a cast of steel.

The photographs reproduced in Figs. D to K are examples of some different types of cracks none of which could be detected except when tested magnetically.

Figs. D and E (Plates 15 and 16) show surface cracks produced by too-drastic grinding of a case-hardened worm wheel and traction pinion respectively. Although the worm wheel shows severe cracking it will be noticed that the cracks all run in a parallel direction at right angles to the axis of the teeth. Fig. E, on the other hand, shows cracks both at right angles to and along the length of the teeth. The lengthwise cracks would, of course, be particularly dangerous at the bottom of a tooth where bending stresses are a maximum, and cracks at right angles as seen in Fig. D would not be dangerous in the same way, though under high specific loads they might result in bad flaking, particularly if they were of the type shown in Fig. F (Plate 16), which is a microsection of a tooth normal to the surface.

Fig. G (Plate 16) illustrates a typical hardening crack at the end of a quenched and tempered traction pinion, again shown up by routine magnetic test after heat treatment.

Fig. H (Plate 16) shows " fatigue cracks " on the ends of all the teeth on a pinion that had been overloaded in service.

Fig. J (Plate 17) shows the end of a large shaft with magnetizing yoke in position, and Fig. K (Plate 17) shows hair cracks on its end. Actually the cracks were first located on a test of the 5-in. diameter bore, the shaft end being subsequently tested and photographed for record purposes. About 35 cracks are shown in the area photographed in Fig. K, but not one of these could be seen without the magnetic test, even after their position was known.

There is another non-destructive test which I should like briefly to mention and which is not referred to in any of the papers, and that is what may be called the "tarnishing test." If a piece of steel is smooth-machined, using paraffin as lubricant, then, on exposure to the air, and as it tarnishes, paraffin oozes out of the cracks and a sort of equilibrium is set up between the rate at which the paraffin oozes out and the rate at which it evaporates. When tarnishing occurs the whole surface goes dark except for small areas round the cracks which have been protected from oxidation by the paraffin. In the case of fine cracks the contrast may be very marked indeed, the position of cracks being clearly marked out provided that one knows what the little light-coloured areas mean. This procedure can be used as a routine test by arranging for tarnishing under controlled conditions.

**Mr. D. A. Oliver:** The research department of the firm with which I am associated was recently faced with a very interesting and special case of non-destructive testing. We were asked to take a finished aero crank and examine it on all its surfaces by a simple method. After carrying out a large number of experiments involving a.c. and d.c. fields, we found that the degree of sensitivity required was very high. One small hair crack $\frac{1}{8}$ in. long is sufficient nowadays to condemn a crank, and to find one tiny hair crack by a rapid method without

using a special jig for every single design is a difficult problem. It was solved in the end quite simply by passing a very heavy d.c. surge current from end to end of the crank. The crank was then permanently magnetized circumferentially so far as the shaft and pins were concerned; and even on the faces of the webs, which were offset slightly from the main axis of current flow, the results were still quite satisfactory. It is only necessary now to pass the surge current from end to end of the crank, immerse it in the fluid, and allow it to drain. The surfaces, which are ground and bright, drain completely when the right oil and the right iron powder are used, and only minute black indications are seen on a bright ground when defects are present.

I agree with Mr. Warren that testing on remanent flux is the most discriminating method, so far as our present experience goes.

With regard to interpretation, we have found that where fine elongated sulphides are present there may be a vague indication of a long crack. If, however, there is a grinding allowance, and a thickness of a few thousandths of an inch is removed, the indication of a possible crack will disappear.

Finally, I would mention that when the physical character of these hairline cracks or flakes is examined the strength across the flake is found to be zero, while in the neighbourhood of the fringe of the flake the full strength is indicated. Working to an accuracy of better than 1 part in 1 000, I have found that there is no change of electrical conductivity across the flake, nor was there any appreciable change of magnetic permeability, to the same degree of accuracy.

**Mr. J. P. Reed:** I should like to ask whether the authors have had confirmation of the anomalies in crack testing by means of magnetic powder that Holdschmidt observed in 1937.* Holdschmidt found that spurious indications identical with those of genuine cracks are obtained if elastic deformation of a cold-worked material is caused by a ferro-magnetic object. He found that ground and hardened crankshafts after having a snap gauge slid along them produced these spurious indications. In the case of cold-drawn carbon and alloy steel tubes, owing to minute variations in the surface of the drawing dies, the conditions related by Holdschmidt may exist; and in fact under my own observation, some time prior to the publication of his paper, some tubular aero-engine push rods were rejected on the ground of indications that cracks were present, the push rods having been tested by the magnetic-powder method. Subsequent microscopic examination of these push rods showed that no cracks whatever existed. There was no question of confusion having been caused by die scratches. I should be interested to know whether anyone else has had similar experience.

Dr. Berthold states that the best sensitivity is obtained when working between ampere-turn figures of 30 and 90. This seems rather summarily to group the $B$-$H$ characteristics of all the steels which may be encountered in practice. It has been my experience that testing for defects is misleading if the flux density in the material approaches the saturation point, and personally I choose a value for $B$ of about 30 % of the saturation figure.

* *Zeitschrift des Vereines Deutscher Ingenieure*, 1937, vol. 81, p. 862.

With regard to the other electrical and electromagnetic methods of testing, I think that it is necessary to be very circumspect. My experience indicates that there must be absolute uniformity of physical structure and magnetic permeability, and not infrequently dimensional variation within normally accepted manufacturing limits is quite sufficient to vitiate the utility of the test. Dr. Berthold mentions Otto and Wever as being able to detect flaws of 0·3 % of the cross-sectional area of a cable. When one considers that a non-metallic inclusion, say of alumina, which constitutes only 0·00001 % of the cross-sectional area of a tube, has been known to cause failure in expanding tubes into a header, the Otto and Wever method seems quite inadequate.

**Mr. A. J. King:** With regard to the first paper, I should like to say a few words about the type of permeameter shown in Figs. 7 and 8 and usually referred to as the "bar and yoke" type. It is stated on page 523 that means are provided to ensure uniformity of field in and near the specimen. As a result of an investigation some 10 years ago, we found that there are four criteria of uniformity of the field in such a permeameter over the central region of a uniform specimen: (1) Absence of variation in $B$ in the specimen along its length. (2) Absence of variation in $H$ near the specimen along its length. (3) Absence of variation in $H$ normally away from the specimen. (4) Equality of the measured $H$ near the specimen with the value calculated from the ampere-turns per centimetre of the main magnetizing coil.

Any one of these criteria may be used, and whichever is satisfied the others are automatically satisfied. Their relative sensitivity is determined by the particular search-coils used. The first criterion has been used by other workers, but my colleagues and I have found that the last one, in addition to having great sensitivity, leads to a much simplified testing procedure. Adjustment of the field in the permeameter to uniformity is effected by compensating for the reluctance of the joints between the specimen and yoke and also of the low-reluctance yoke, by the addition of extra ampere-turns at the ends of the main magnetizing coil near the joints. The addition of the right amount of compensation together with the low-reluctance yoke makes the main coil behave, at its centre, like an infinitely long solenoid, so that the agreement between the measured and calculated $H$ and the field uniformity follow naturally. This technique enables testing to be carried out at round numbers of $H$ which can be printed beforehand on test sheets together with the corresponding main-coil currents. A further simplification is possible since, with the specimen removed, the low-reluctance yoke closed, and no compensation current, the field in the main coil is uniform and serves to calibrate the $H$ search coils and galvanometer. For a given apparatus, therefore, the $H$-coil deflections can also be printed beforehand, and all that is necessary when a specimen is inserted is to reproduce these deflections for each test point by adding compensation only to the predetermined main-coil excitation. With a carefully wound main magnetizing coil the turns per centimetre can be known with sufficient accuracy to enable the field in the specimen to be adjusted to the desired value within 1 %. The flux in the specimen is then determined in the usual way by a search coil, or, as indicated in the paper, for

thin strips by a $B$–$H$ coil, which obviates air-flux corrections.

The effects of cutting on the permeability of thin strips is noted in the paper. That the 10-cm. wide strips used in the above permeameter are wide enough to make the effect negligible was demonstrated by testing such a strip whole and then successively after cutting longitudinally into 2, 4, and 8 equal strips. This effect of cutting on permeability is usually a maximum in the region of $B = 13\,000$, but with 10-cm. strips it is usually less than 5 %. In bar materials there is much to be said for a round rod specimen, which can be readily tested in such a permeameter by means of adaptors to make a good joint with the yoke. To reduce cutting effects the rod should be turned in a lathe with a sharp tool. Such a rod, of 0·5 in. diameter, can be seen in a position protruding from the yoke in Fig. 8. A detailed description of this type of permeameter by Mr. A. M. Armour will be published in the near future.

Regarding the magnetic methods of fault detection, as indicated on page 525, search-coil methods are particularly adapted to the location of deep-seated faults, while iron-dust methods are best suited to the detection of surface faults. In both cases the action is dependent on the extent of the field distortion caused by the fault and the sphere of response of the detector. When using search coils it is a great advantage to explore with a differential pair, i.e. two spaced coils connected in opposition, as this reduces enormously the effect of irrelevant factors. The spacing of these coils should be fixed from a knowledge of the spread of the field distortion due to the type and depth of faults sought, so as to give a good sensitivity. This method lends itself particularly to the testing of continuous uniform cross-sections.

Turning to iron-dust methods, while my colleagues have in this way revealed the presence of cavities and bolts $\frac{5}{8}$ in. below the surface, it is of much more moment that they easily reveal surface cracks too small to see with a magnifying glass. The translatory forces on the minute iron particles in the vicinity of such small cracks are very small, often less than the gravitational forces on the particles. It is therefore a great help in such cases to have the particles in suspension in a suitable fluid medium, in particular one having a density high enough to relieve appreciably the gravitational forces and yet with a low viscosity so as to facilitate movement of the particles. These two considerations are in general, mutually antagonistic, but a good compromise is given by a light oil. To keep the translatory forces as large as possible it is better, in general, to cover the specimen with the detecting fluid suspension while the magnetic field is being applied: however, when the length of magnetized path and the coercive force of the material are sufficient, it is permissible to use the remanent magnetization. This probably explains the experience of Mr. Warren and Mr. Oliver, who prefer to use the remanent field. They probably test comparatively large articles, where the remanent magnetism is sufficient; but experience in detecting longitudinal cracks in small articles, such as aero-engine gudgeon pins and valve springs, indicates that it is essential for the utmost sensitivity to test with the applied field. Even when these points have been given due consideration it is advisable, in order to detect the smallest cracks, to re-test the article the other way up, as this takes advantage of the slowly falling particles. As a final help, the article should be allowed to stand and drain before examination.

By attention to all these points the range of the method in finding extremely fine cracks can be very much extended. Where cracks run in more than one direction the article must be magnetized so that the magnetic flux crosses all cracks. This can be done in separate tests, each with its own inspection, or with one inspection after the necessary multiple magnetization and application of fluid. The latter procedure calls for care, or the record produced by one magnetization may be obliterated by the next. A convenient universal apparatus for carrying out either successive tests with mutually perpendicular fields or for simultaneous testing with a roving spiral magnetization is illustrated in Fig. 13 (Plate 2). That the very minute cracks are important has been demonstrated conclusively by an analysis of the breakage figures on aero-engine valve springs before and after the installation of the testing apparatus shown in Fig. 15.

Before I pass on to the next paper, it may be well to issue a warning against the confusion with a crack of a manifestation of what electrical instrument makers call "the screw driver effect," and what broadcasting engineers know as magnetic tape recording. It depends on the ease with which a piece of fairly hard magnetized steel can retain a very localized increase or decrease in magnetization, e.g. if a corner of a hard magnetized article is drawn across the surface of another such article a line similar, at first sight, to that due to a crack shows up when detecting fluid is applied. The effect is strikingly demonstrated by the portable detector of Fig. 16 (Plate 1) and a pointed magnet. The effect is removed by remagnetization, but the moral is: When letting articles drain after magnetization and before inspection, do not let them touch each other or any other magnetic bodies.

With regard to the second paper, I should be interested to learn more about the experimental arrangements for obtaining the curves of Figs. 2, 3, and 4. Also, I do not understand the units used as ordinates in Fig. 5, especially as a d.c. curve is included.

On page 532, in the section headed "Demagnetization," the author states that all articles which are eventually used as moving parts must be carefully demagnetized after testing. While this is good general advice, I cannot agree that it is essential with such things as gudgeon pins which have been magnetized only circumferentially, since transverse faults are so unlikely, by current through a central conductor. If such an article is sound, there is no non-destructive way of determining whether it is magnetized or not; and if, owing to a crack, it displays a stray field, it is rejected. The last sentence of this section is not clear, as all articles are magnetized to some extent by the earth's field.

The opening sentence of Section (2) seems at variance with Figs. 1 and 3 and with the experience I have recorded above of detecting cavities $\frac{5}{8}$ in. below the surface. It is obviously a question of degree.

My colleagues and I had occasion to test an apparatus similar to Fig. 15, but using bar magnets for excitation

and a telephone instead of an instrument as the detector. We had no success, as we could not get it to detect an unwelded butt joint between two plates. The reliance on telephones in a fabrication shop, one of the noisiest spots on earth, was a bad feature, and no doubt the use of an instrument such as the detector constitutes an improvement.

There is one method of non-destructive testing which seems to have escaped mention, and that is the straightforward electrical fall-of-potential method. We have recently applied this successfully to the welded joint between a head and a shank. We passed a heavy direct current through the joint and measured the millivolts across it with a sensitive instrument. After 20 joints had been tested, they were broken in two at the weld and very good agreement was obtained between the conductivity figures and the goodness of the welds. As a result a routine test was instituted which is proving very valuable. I am indebted to Mr. A. M. Armour for much of the experimental work I have quoted above.

Regarding the paper by Dr. Dorey, I am glad to see that he issues a warning about relying too much on the "tapping" test, because of an experience my colleagues and I had a few years ago when trying to create an internal fault in a large wheel by drastic heat treatment. We finally succeeded, and, with a gaping crack in it, the wheel rang as well as it had done before cracking.

The author does not seem to be quite clear on page 553 about the respective functions of objective noise meters and noise analysers. The former measure only the overall magnitude of a noise, whereas the latter pick out the components of a noise and measure them in frequency and magnitude with a view to finding out their causes. There is no doubt about the usefulness of the latter apparatus, as was shown in a paper* read before The Institution by Mr. B. G. Churcher and myself in 1929, and since then the method has been applied to a wide range of products from quiet house service meters to the noisiest of warning sirens.

Regarding the use of supersonic methods, suggested by Dr. Davis, they are applicable to the detection of transverse faults in long uniform sections, but this problem seldom occurs in practice. Usually the only places where it is important to look for transverse faults are in forgings and castings where there are changes in either cross-section or direction, and these cases do not lend themselves readily, in general, to supersonic methods.

**Mr. J. D. Hannah:** With regard to Prof. Thornton's method of assessing thickness, during the last 10–12 years the firm with which I am associated has applied this method to give a measurement of resistance for distinguishing between steel bars of different compositions. In the course of developing this application of the method I made an investigation into the effect of the thickness of the bar, and found results somewhat similar to those of Prof. Thornton. I found that it is possible to distinguish between a plain carbon steel and a 2 % nickel steel quite satisfactorily for sorting purposes, even if the bars concerned differ appreciably in thickness.

I should like to ask the authors of the papers on magnetic testing whether any mechanism has been developed for continuous handling of tests on steel strip.

* *Journal I.E.E.*, 1930, vol. 68, p. 97.

Mr. Benson raised the question of tarnishing tests; I have come across a similar phenomenon in regard to parts which have been tempered in salt baths and subsequently cleaned by shot-blasting. If the parts are permitted to rust slightly, it is found consistently that rust does not form over the site of a crack: presumably the salt used for tempering exerts some slight protective influence at such a position.

**Mr. W. J. Sulston:** Dr. Fleming and Mr. Churcher refer to methods of making contact with materials when measuring permittivity and power factor, and state that colloidal carbon backed by a metal plate is suitable at low frequencies. At the Post Office Research Station we have found that a considerable improvement is to use colloidal carbon backed by mercury.

The use of metal foil or metal-sprayed electrodes is an improvement over systems previously employed. In the former case, however, at some frequency—depending upon the capacitance being measured—the series resistance of the foil and of the contact between the foil and the metal plate become important, and then alternatives have to be sought. The use of metal-sprayed electrodes is not always suitable. There are two other methods by which the power factor can be determined. The first is to use plain metal electrodes, in which case we obtain a capacitance (which may be regarded as a pure air capacitance) between the electrodes and the specimen, and a correction can be applied to the observed power factor. Thus, if $\tan\delta$ = observed loss tangent, $C_m$ = measured capacitance, and $C_s$ = true specimen capacitance, then

$$\tan\delta_s = \text{true loss tangent} = \frac{C_s}{C_m} \times \tan\delta$$

This method breaks down if the surface conductance in the specimen is appreciable, i.e. if the specimen is not flat. The obvious method of overcoming this difficulty is to obtain flat specimens, but this is not always possible.

An alternative which we have used is to insert the specimen between metal plates having a separation $d$ cm., greater than the thickness of the specimen, $d_1$ cm. Then if $A$ = area of plates, in cm²; $A_1$ = area of specimen, in cm²; $C$ = capacitance, in $\mu\mu$F, between the plates with air as dielectric; $\Delta C$ = change of capacitance, in $\mu\mu$F, on inserting specimen; and $\Delta G$ = change of conductance, in reciprocal ohms, on inserting specimen;

$$k = \text{permittivity of specimen} = \frac{\dfrac{A_1}{A} + \dfrac{\Delta C}{C}}{\dfrac{A_1}{A} - \dfrac{\Delta C}{C}\left(\dfrac{d}{d_1} - 1\right)}$$

$$\text{Power factor} = \frac{\Delta G}{\omega} \cdot \frac{kA_1}{3\cdot 6\pi d_1} \cdot \frac{10^{12}}{\left(\dfrac{A_1}{A}C + \Delta C\right)^2}$$

These equations take no account of the distortion of the electric field which will be caused by the insertion of the specimen, and the permittivity determined by this method will therefore be in error. This error will normally be quite small, however, and the effect on the power factor will be negligible.

**Dr. G. Shearer:** I am glad that the authors emphasize the need for first-class technique and skilled interpreta-

tion. Unfortunately, I think that we must be prepared to admit that an object which has satisfactorily passed a radiographic test, even when that test is carried out by a skilled and experienced investigator, may still contain a vital flaw, while if the technique employed has not been of the highest quality the probability of such an occurrence is, of course, greatly increased. A considerable amount of work still remains to be done in the study of the various types of defect revealed by radiography, with a view to discovering how important these defects are in relation to the subsequent use of the material, and how much tolerance is to be permitted with a given material. In this connection a co-operative research undertaken jointly by engineers and X-ray specialists might well yield useful results.

I should like to refer to the X-ray diffraction method of non-destructive testing mentioned briefly by Mr. Pullin. Many of the properties of a material depend upon the nature of the crystallites which go to its formation. For some purposes a coarse-grain material is desirable, while for others it is important that the grain size should be as small as possible. By the use of X-ray analysis much information is immediately obtained as to the crystal grain size, even when the crystallites are far too small to be seen under the microscope, and variations in grain size resulting from unequal heat treatment can of course be detected by this method.

Directional processes, such as heavy rolling, produce in a material a structure in which the individual crystallites tend to set themselves in some particular direction, so that the final material will often have very different properties in different directions, whereas if the crystallites were oriented at random the properties in all directions would be identical. This fibre structure is of very considerable importance in connection with certain magnetic materials, and is easily detected and interpreted by X-ray diffraction methods.

For certain purposes—for example, the steels used in the cores of transformers—it is important that the crystallites should be as perfect as possible, whereas for other purposes, such as magnet steels, we very often want crystallites which are highly imperfect. A material with good crystals gives an X-ray diffraction pattern in which the lines are sharp and clearly defined, whereas if the crystal lattice has undergone a strain the lines of the diffraction pattern become correspondingly blurred. This blurring is to some extent a measure of the amount of strain in the crystal lattice. Under suitable conditions, different degrees of strain at different parts of the specimen can be detected.

The recent work of Gough and Wood on the fatigue failure of metals is a good example of co-operation in research between the engineer and the physicist. The changes in the pattern of a material subjected to alternating stresses are of such a nature that for a given material it should be possible to predict whether there is a danger of fracture long before the fracture stage is reached.

In these days, when complex alloys are frequently used, it is essential that the alloy should have the proper structure and not merely the proper chemical composition. Particularly in the case of ternary alloys, which are very sensitive to heat treatment, X-ray examination probably provides the easiest and most certain way of determining whether the correct phase, or combination of phases, is present in the resultant material.

X-ray diffraction methods can be used in cases where chemical analysis is difficult or will not readily give information of the type desired. For example, when two substances are combined they may exist as a solid solution, as a physical mixture, or perhaps as a new compound. X-rays immediately differentiate between the three cases and tell us which particular combination has occurred. Again, a substance may exist in more than one crystalline form, and it may be, and often is, the case that one form is suitable for a definite purpose and the other entirely unsuitable. Chemical analysis, of course, does not differentiate between these two as such, but the X-ray diffraction method gives entirely different pictures, according as one or the other or both are present. In the examination of refractory materials, where there are very considerable difficulties in chemical analysis, the use of the X-ray diffraction method is often a very valuable supplement to the results of the more ordinary, chemical tests.

**Dr. R. Berthold:** When discussing Fig. 6 in his paper, which indicates the relationship between the ratio of the intensities of scattered and direct radiation and the thickness of steel, Mr. Pullin remarks that the effects of scattered radiation are magnified by salt screens in the resulting radiographs. I believe this conclusion to be incorrect. Mr. Pullin has derived the ratio of the intensities of the scattered and direct radiation from exposure curves, i.e. comparisons of the exposure times with and without additional scattered radiation which are required to give an equal degree of blackening of the film, and I expect he has neglected the Schwarzschild exponent. The ratio of the intensity of the scattered radiation to that of the direct radiation may be calculated from the equation:

$$\frac{I_d + I_s}{I_d} = \left(\frac{t_d}{t_{d+s}}\right)^p$$

where $I_d$ and $I_s$ are respectively the intensities of the direct and the scattered radiation, $t_d$ is the exposure time without scattered radiation, $(t_{d+s})$ is the exposure time with scattered radiation, and $p$ is the Schwarzschild exponent. The Schwarzschild exponent is unity when the film is entirely blackened by means of X-rays; it is smaller than unity when the film is blackened by means of fluorescence from the intensifying screens. This, in my opinion, explains both the difference found by Mr. Pullin and the conclusion (page 569) of Messrs. Lester, Sanford, and Mochel that when intensifying screens are used the inverse square law does not hold for the distance between the source of X-rays and the film.

**Mr. W. B. Shannon:** I should like to raise one general point in connection with non-destructive testing in relation to X-ray examination. When testing destructively it is usual to take a sample from a whole component, or, if there are a large number of components, to take a percentage of that number, and, depending on the result of the destructive tests of these representative samples, the whole consignment is either rejected or accepted.

Fig. 9 of Mr. de Graaf's paper shows the influence of X-ray inspection on the quality of the welds in German bridges over a period of about 1 year. I believe that

similar experience has been obtained in this country. Where there are a large number of welds, as on steam-pipe ranges, is it satisfactory and safe to test a percentage of those welds by the X-ray method? The procedure followed by some firms in this country when fabricating welded drums is to test each inch of weld by the X-ray method, and that procedure has reduced the number of repair welds required on such drums. It would appear that it is equally necessary for X-ray inspection to be carried out on every steam-pipe weld, as distinct from a percentage number or a portion of each weld. The effects of a failure on a steam range would, of course, be very serious. With any type of percentage testing, whether or not using destructive or non-destructive methods, the element of uncertainty regarding the parts left untested is not entirely removed.

I should like to ask Mr. de Graaf whether it is possible and easy to carry out an X-ray inspection of a positional steam-pipe weld, a weld which is made perhaps adjacent to the wall of a boiler house, with a short distance between the pipe and the wall.

There is a reference on page 577 to overspeed testing of turbine units. It would be interesting to know whether the method employed was to run the turbine up to an agreed overspeed only, or whether, in addition, the practice was followed of throwing load off the turbo-alternator when the turbine had been operating at, say, maximum continuous rating.

I also suggest that in many cases the manufacturing process applied to components made with good sound materials is, in effect, a most searching non-destructive test.

It may be of interest to record that in connection with a large consignment of alloy-steel bolts most of the usual destructive tests had been applied in order to discover the reasons for breakages which had occurred with a few of these bolts in service. Eventually the magnetic test, using the powder method, was applied in order to verify whether cracks were present. As the bolts had been in service for some years they had become scaled, and before the test was carried out it was necessary to loosen the oxide and corrosion products to facilitate cleaning operations. The bolts were pickled and thoroughly wire-brushed, so as to obtain the maximum degree of sensitivity in their reaction to the magnetic testing. When the test was applied, the most minute surface blemishes were disclosed on the bolts. The test enabled uncertainty regarding the bolts to be eliminated, as any longitudinal markings which were shown up by the magnetic test were proved to be of no measurable depth, having no mechanical or metallurgical significance. As a result of the test the bolts, which were suspect on account of embrittlement tendencies, were reheat-treated and restored to service.

**Mr. R. Le Rossignol:** Normally we employ about 20 milligrammes of radium when gamma-ray testing; with such a small quantity it is not difficult to provide protection for the operators. We start the exposure overnight, and by the next morning have an excellent gamma-ray photograph. It is possible with gamma rays to determine the height of liquid in machinery which is working, and we have successfully applied the method to an absorption refrigeration machine the metal parts of which are over $\frac{1}{8}$ in. thick. It would be almost impossible to make such a test by means of X-rays, because one could not get the X-ray plant near enough, and if this difficulty were overcome the working of the machine would be so much affected that it would give erroneous results.

**Mr. W. J. Wiltshire:** If X-ray testing is to be employed in shops and factories, safety both from radiation and from electrical dangers is of paramount importance; it was only comparatively recently that reliable apparatus became available which could be put into shops and worked by people of no particular scientific qualifications.

Mr. Pullin said that he did not think a higher voltage than 300 kV would ever be necessary for radiological testing. I am inclined to think, however, that still higher voltages can be usefully employed. When working near the upper limit one is forced to try to reduce exposure times by bringing the X-ray tube too near the specimen, and one is tempted to use the most rapid intensifying screen obtainable. Unfortunately, such a screen generally has a coarse grain, and the definition therefore suffers. If, on the other hand, more power and a higher voltage are available, such extreme measures are unnecessary. A fine-grain screen may be employed; one can even use (as we are using so much now) lead foil as an intensifying screen.

The problem of scatter is a very big one. We can use a grid diaphragm to deal with it, but then the exposure time goes up enormously unless we can increase the voltage. It is true that with higher voltages we lose contrast to some extent, but if we use our scatter-reducing devices the reduction of scatter results in a gain in contrast which counterbalances, to some extent, the loss due to increased voltage. I think, therefore, that it pays to be able to use very high voltages, and I would put the present limit at 400 kV rather than 300 kV; I will not say that even 400 kV will be the ultimate limit.

One of the most important of coming developments in radiological testing is the use of radium emanation instead of the radium salt as the source of gamma rays. This should enable us to obtain a standard of definition comparable with that given by an X-ray tube. Another line of research which I feel is very important is the development of the visual fluoroscopic method and the cutting-out of the photographic process. We need, in addition to new intensifying screens, an improvement in fluorescent screens and in the methods of using them. I am inclined to think that we are faced with the same problem here as in the case of intensifying screens, extra sensitivity meaning loss of definition.

At present, while we can tell the area of a flaw from the radiograph, we cannot tell what it really represents in loss of metal, or loss of strength. I think that ionization methods may ultimately prove in certain cases a help towards the solution of this problem, which is made more difficult by the existence of scatter. We at Woolwich have found that the amount of scatter increases very much with the thickness of the specimen, but, over the very limited range of voltages at which, at present, measurements have been made, it does not increase with the voltage. The probability is that, as the voltage increases, scatter becomes less troublesome. This is actually true in the case of the radiation emitted by radium.

I am pleased to see from the paper by Messrs. Lester, Sanford, and Mochel, that the question of the penetrameter has recently received further attention in America. On the Continent, Mr. de Graaf tells us, a wire type is used. This is subject to the disadvantage that the visibility of a wire depends on its length. We have used a step penetrameter with very small holes, so that we are really observing artificial flaws. Their arrangement indicates their thickness, and so the instrument is easily read with certainty even under "rush" conditions.

**Mr. R. A. Stephen:** I should like to refer to some practical points which arise in the examination of circumferential seams of boiler drums. The normal practice has been to photograph such seams from the outside, whereas it is clearly better from the technical aspect to take photographs from the inside. In the latter technique the rays always traverse the same thickness, and all, or one-third if desired, of the circumferential seam can be taken in one exposure. With the beam firing from the outside of the drum many photographs must be taken to cover the whole seam, and the photographs are inferior in quality and sharpness. Drums vary appreciably in diameter—the smaller the diameter the bigger the advantage with the inside technique.

The field of industrial X-ray testing may be divided into two categories: (1) the photographic method, used principally in the testing of welding and to a certain extent in the testing of castings; and (2) visual, used chiefly in aeroplane and light-alloy work. The conditions required for fluoroscopy are quite different from those required for photographic X-ray work.

It would be of interest to know for the latter class of work whether Mr. Pullin considers that emphasis should be laid on the necessity for X-ray tubes of low filtration, which seem to be necessary for the screening of magnesium.

I should like to mention that the number of radiological testing plants available in the U.S.A. is about 55–60, whereas Germany has over 300, and England about 100. In Germany, with 300 or more X-ray plants in use, the question of interpretation is bound to have arisen. What degree of skill in interpretation is necessary for practical work, and what measure of control is exercised by authoritative bodies? I should like to ask Dr. Berthold whether travelling inspectors supervise in Germany the interpretations made by local operators, and for his views on this subject.

I notice that the exposure curves given in Mr. Pullin's paper for the use of lead screens with 200-kV radiation involve an exposure time of about 140 minutes for 2 in. of steel. Such a time is permissible only for laboratory work, but it is far too long for practical purposes. It seems possible to effect an improvement in the quality of photographs of thick material by using a heavy metal filter under the specimen with normal intensifying screens.

It seems evident that a number of rather difficult problems have to be solved in connection with scattered radiation. Manufacturers can produce plant intended for voltages up to 400 000 volts or more, but the protection required in works when such high voltages have to be used is another question. At voltages up to 300 kV, provided one works at a reasonable distance from the object, one is safe, bearing in mind the number of photographs usually taken per day; but at higher voltages there may be danger on account of the large amount of scatter which will be present.

As far as the usual methods of X-ray inspection are concerned, the international recommendations for X-ray protection may be misapplied. Data for lead protection usually assume the operator to be at a distance of 1 metre from the tube. In industrial practice, however, it is customary to work at 16 in. or even 10 in. from the tube, and it seems to me that data should be provided regarding the necessary thicknesses of lead for adequate protection at varying distances with varying voltages up to 200 kV.

**Mr. R. Seifert:** I agree with Mr. Pullin about the difficulties involved in the visual X-ray examination of aluminium and other light-alloy castings. I have this year introduced a new method in Germany for the visual X-ray examination of magnesium alloys. I use an X-ray tube with a focal point of about 0·1 mm.; this makes it possible to magnify the test specimen on the screen up to 10 times and to see sharply on the screen defects which are not visible when using the normal method of screening, which shows on the screen nearly the original size of the specimen. Instead of pulsating direct current I use constant direct current.

**Dr. W. Betteridge:** I endorse what has been said as to the need for improvement in screens for the visual examination of materials, particularly aluminium alloys. Visual examination is found to be satisfactory at present for detecting such gross errors as blowholes and shrinkage cavities, but there is a type of fault in aluminium castings which can be detected only by photography, and that is the fine porosity due to dissolved gases being emitted on solidification of the metal. This fine porosity can cause a very noticeable reduction in the strength of the metal. Another type of fault is the segregation of the alloying constituents in the metal. The heavy-metal additions (such as copper and nickel) which are customarily made to aluminium tend on solidification to migrate to the edges of the crystal grains. If the rate of solidification is slow this segregation can be easily detected by radiography, but it is not visible on the fluorescent screen. It can cause reductions in strength of the aluminium alloy up to 20 %. I have also found segregation of this type in cast stainless steels containing large amounts of chromium or tungsten; the alloying metal separates in just the same way, with a notable reduction in the strength of the material.

**Dr. A. H. Davis:** Generally speaking, present-day acoustical testing may be divided into the following groups: (i) Measurements of the overall performance of the varied wanted and unwanted sound-producing devices, such as telephones, loud-speakers, motor horns, motor-car gears, pneumatic drills, noisy machinery, and engine exhausts. (ii) Tests of the acoustical properties of materials, such as vibration insulators and absorbent materials for correcting echo and reverberation. (iii) Measurements of sound transmission by walls, floors, building structures, water pipes, underground tunnels, etc. (iv) Analyses or other recordings to determine the components of the noise from sources, such as vacuum cleaners and motor exhausts, with a view to ascertaining from the constitution of the noise the best method of

suppressing it. Faults in machinery may often be diagnosed by taking simultaneous records of the sound emitted and the cycle of operations.

Acoustical tests are not yet used to any considerable extent for determining the mechanical properties and defects of materials. Possibly the difficulty of using sound as an exploring tool for detecting faults is that sounds of medium pitch spread easily around corners or around faults. It seems, therefore, that acoustical testing should be more fruitful at very high frequencies, where sound travels more nearly in a straight line, like light. In this connection it is interesting that nowadays it is possible to set bodies in vibration at "ultrasonic" frequencies, i.e. at frequencies much above the range of the human ear.*

When light is passed through a solid or a liquid which is being subjected to ultrasonic vibrations, the light is diffracted much as it would be from an optical grating. When a circular beam of light is passed through an excited material the image focused on a screen consists of two concentric rings. The diameter of the inner ring is determined by the longitudinal waves in the sample, and the diameter of the outer ring by transverse or shear waves. From the diameters of the rings it is possible, for isotropic bodies, to determine all the elastic constants from a single sample of the material. Moreover, the shape of the sample does not affect the character of the pattern.

Many kinds of glass have been studied by these means, and similar results can be obtained with opaque bodies using reflected light. In another application of ultrasonic waves mentioned by Sokolov a beam of high-frequency waves is passed through a sample of metal whose soundness is in question, and is detected by a small vessel containing liquid, through which light is passed to give a diffraction pattern. A homogeneous sample of metal gives a clean pattern, while a blurred result is obtained with a defective piece. These achievements indicate that ultrasonic waves may have useful applications in non-destructive testing, where it is desired to determine the elastic constants of a material, or to test a sample for defects. I should be interested, therefore, to learn whether the authors or other persons present have experience of any success obtained in this field.

**Dr. H. S. Simons:** Dielectric testing is employed mainly for testing materials for use in the electrical industry, but there is the possibility of using the dielectric constants and properties of materials also for general chemical and other tests. Any kind of material including conductive or electrolytic substances, can be tested as a dielectric provided it is placed between the two electrodes so as to prevent the measuring system from being short-circuited. I should like to show some applications of the dielectric method and some diagrams obtained by a special instrument, the dielcometer. Tests can be made by means of this instrument in periods of the order of minutes, and by such tests it is possible, for instance, to follow the whole process of ageing of the material, so that a sample of correct age can be taken as a comparison and standard (see Fig. L). The moment the instrument shows that the right age of the test material has been reached, its manufacture can begin.

* See L. Bergmann: "Ultrasonics" (G. Bell, 1938).

The method can also be used for testing the percentages of two substances in a mixture. If the mixtures are not homogeneous it may be necessary to work at a higher temperature, or to dissolve the mixture. In some cases special arrangements have to be made so that the inhomogeneity of the test body can be dealt with.

**Dr. C. H. Desch:** I should like to say a word on the acoustic method of testing, which seems to have great possibilities, but I would first call attention to the historical aspect of the matter.

The work of Robin, which was done about 30 years ago, seems to have been altogether overlooked. He used the simple method of suspending bars, striking them, and measuring the time during which the note remained

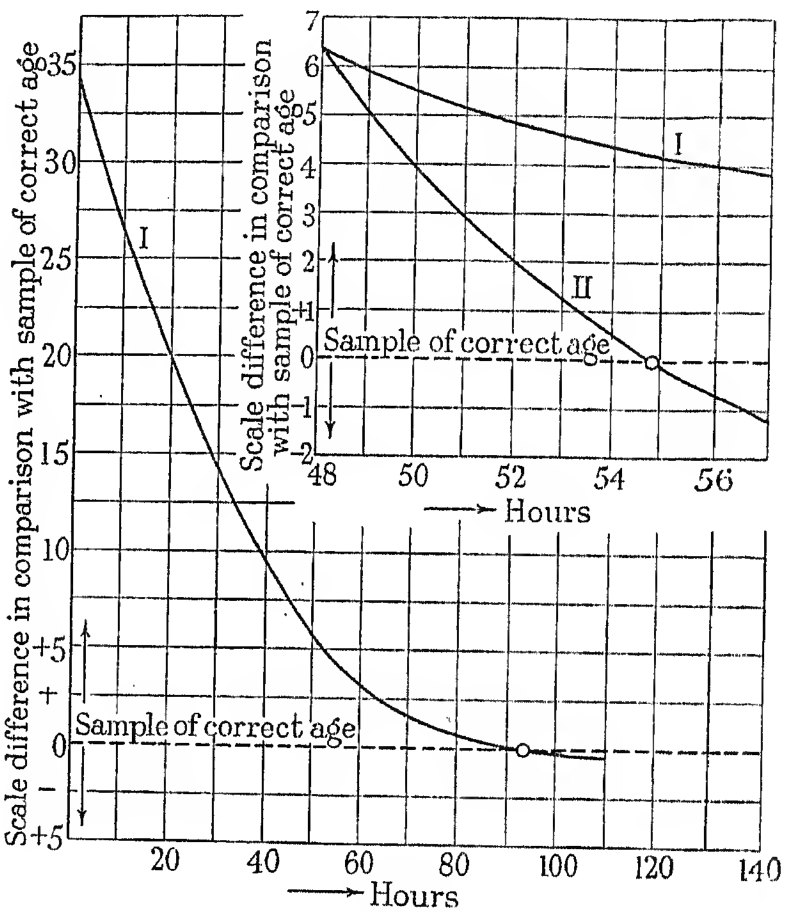


Fig. L.—Ageing of an alkaline cellulose, determined by dielcometer analysis.
Curves I.—Measurements at 20° C.
Curve II.—Measurements at 40° C.

audible; and in that way he was able to determine the influence of temperature on the modulus and on the damping of a great range of steels. He showed, for example, the great difference between alloy steels and carbon steels in respect of their temperature-coefficients of damping. Further work on the subject has recently been done by Miss Waller, who excites the natural frequency of the bar by the very pretty method of holding against it a pointed block of solid carbon dioxide. She has investigated the change in the modulus and damping over a range of temperatures and compositions. This method will have advantages if one can overcome the difficulty, referred to by Dr. Davis, of the sound so easily going round corners. By using supersonic waves it would seem that one ought to be able to determine the presence of deep-seated flaws in forgings. In an ordinary forging or structure there are so many different modes of

vibration, however, that the problem may be too complicated.

An urgent need of the metallurgist in non-destructive testing is a method of determining the internal stress in masses of metal. By various methods of cutting it is possible to find out the internal stress due to differences of temperature during cooling or to internal transformations (phase transformations) in the alloy.

I should like to know what Mr. de Graaf thinks of the usefulness of the X-ray method as a means of determining internal stress. If one takes a stressed object, such as a cold-drawn bar of steel, and sections it and then makes a very careful map of the hardness throughout the section, one finds that the hardness varies in a curious irregular fashion; it follows that the stresses must be distributed also in a rather irregular way. It is possible by any non-destructive method available at present to determine the distribution of those stresses?

**Mr. W. C. Heselwood:** Dr. Dorey, referring to the "spark test" method of estimating the carbon content of steels, states that "the test is purely qualitative and then only within wide limits." In actual fact it is regularly used to give the carbon content within quite close limits—within a range, say, of 0·05 %. In some cases, more particularly low-carbon steels, it is also possible to detect the presence of special alloy constituents such as nickel, but attempts to estimate the amounts of such elements should be discouraged because they may be deceptive.

The "spark test" and the "Spekker Steeloscope" are really complementary in a steel warehouse. The former gives the carbon content, but is unreliable for the estimation of other alloying elements; the latter does give these other elements—nickel, chromium, tungsten, molybenum, etc., as stated by Dr. Dorey—but gives no indication of carbon content.

**Mr. W. E. Hoare** (*communicated*): Concerning non-destructive methods for measuring the thickness of the tin coating of tinplate, at the present time measurement is carried out chiefly by the methods of gravimetric or volumetric analysis. As far as thickness of coating is concerned, tinplate is a rather variable product and extensive sampling is necessary in order to provide an accurate estimate. Such methods therefore tend to be rather laborious and expensive. However, the fact that tinplate consists of a non-magnetic coating of tin on a magnetic basis material of mild steel, brings within the bounds of possibility the use of rapid, non-destructive magnetic or electromagnetic methods.

One method of approach is by measuring the force necessary to pull a magnet away from the surface of the material. This principle has been used by C. E. Richards* in this country and by Brenner in America. The latter work is mentioned in the paper by Messrs. Lester, Sanford, and Mochel.

In collaboration with Dr. B. Chalmers† I have used a similar method for contouring the surface of tinplate. The method is sensitive, under the best conditions, to variations of the order of 0·00001 in. in coating thickness. This figure gives approximately the sensitivity required in a tinplate instrument. Usual grades of tinplate have a coating thickness of less than 0·0001 in., and a suitable instrument must be able to appreciate differences of, say, 10 % of this, i.e. 0·00001 in.

* *Journal of the Society of Chemical Industry*, 1937, vol. 56, p. 343.
† *Journal of Scientific Instruments*, 1937, vol. 14, p. 248.

For workshop and industrial use, however, the influence of certain variables (particularly vibration, and variations in the characteristics and thickness of the steel basis) seems to preclude the use of this principle in the design of an instrument suitable for the routine inspection of tinplate. An electromagnetic method, much more suited to routine inspection work, has been devised by my colleague, Mr. W. H. Tait.* The principle is simple, consisting of causing the non-magnetic coating to affect (as an air-gap) the efficiency of a small transformer. With constant input to the primary, the thickness of the coating is therefore related to the output from the secondary.

Owing to the extreme sensitivity required and to desiderata of cost and foolproofness, many difficulties have been encountered, but the majority of these have now been overcome. One of the chief of these difficulties, the ensuring of a very stable a.c. input to the primary of the exploring transformer, has been overcome by an ingenious method worked out in the laboratories of Salford Electrical Instruments, Ltd. Variation in magnetic properties of the mild-steel basis material must also be compensated for. One method has been found which works successfully but which is a trifle inconvenient, inasmuch as manual adjustment is necessary before each observation is made. An alternative automatic method of compensation for varying characteristics of the steel is now under test. With these two major obstacles overcome, it is felt that in due course a satisfactory instrument will be at the disposal of those who have to provide for the routine inspection of tinplate.†

**Prof. Willis Jackson** (*communicated*): The method developed by Dr. Förster and Dr. Köster for studying the elasticity and damping of materials interests me particularly because of its similarity in principle to the "change of frequency" method of measuring dielectric loss, to which I have given some attention and to which Dr. Fleming and Mr. Churcher have referred. I agree with the latter as to the greater convenience of the "change of reactance" method where this can be adopted. The electrode arrangement shown in their Fig. 5 eliminates in very a satisfactory manner the danger of error—and it can be serious if adequate precautions are not taken—likely to arise from self-inductance in the vernier-condenser branch and mutual inductance between this branch and the leads to the main condenser.

The time is ripe for an extension of the aim, revealed in the work of Dr. Förster and Dr. Köster, to develop more scientific methods for studying the mechanical properties of materials, so that these properties may in due time be expressed in terms of quantities to which it is possible to attach "an exact physical meaning." The need for this is particularly marked in the case of amorphous materials, a class of materials to which many notable additions have been made during recent years and which is finding an increasing range of engineering application. It is to be regretted that attention has not been

* *Journal of Scientific Instruments*, 1937, vol. 14, p. 341.
† Further reference to this subject may be found in the following papers: B. Chalmers, W. E. Hoare, and W. H. Tait: Technical Publication I.T.R.D.C., Series A, No. 66; W. E. Hoare and B. Chalmers: *Journal of the Electroplaters' and Depositors' Technical Society*, 1937–38, vol. 14, p. 113; W. H. Tait: *ibid.*, 1937–38, vol. 14, p. 108.

drawn in the various papers to the important work which Houwink, in particular, is doing in this field. As has been mentioned elsewhere,* knowledge of the electrical mechanisms underlying dielectric behaviour has advanced sufficiently for it to be possible to make reasonable anticipations as to the electrical properties of a material from a knowledge of its chemical composition. Thus the very low dielectric loss exhibited by polystyrene and polyethlylene, and the relatively high power factor of bakelite and the chlorinated hydrocarbons, are to be expected from their respective chemical constitutions. On the other hand, there is not as yet any very satisfactory basis for explaining the physical and mechanical properties of these, and other, existing materials, or of forecasting the same properties for new ones.

I should appreciate an expression of opinion from Dr. Förster as to the physical mechanism underlying the damping of vibration in solids. In a recent study of the free torsional vibration of thin rods of a number of materials,† I observed that the amplitude decay corresponded to a constant loss of energy per cycle, and therefore to an "internal viscosity constant," on the classical theory, varying inversely as the frequency. It is clear that this term has no real significance, but the references by various workers to "solid friction" as an alternative explanation appear to me to be equally nebulous and unsatisfactory.

**Mr. H. B. Swift** (*communicated*): Dr. Berthold draws attention to the importance of the relative strength of the magnetic flux with respect to the area of cross-section when testing for cracks or flaws in iron or steel parts. This is a point frequently lost sight of by workers, and may lead to the acceptance of parts which otherwise should be rejected. Tests which I made some years ago showed that while the degree of flux density was not intensely critical, it had to be maintained to a degree just short of the saturation point in the *B–H* curve. Unless this was done there was a distinct danger of the lines of magnetic force failing to be expelled from the crack and forming the desired polarity. For this reason it was evident that ample means of adjusting the magnetizing current in the apparatus must be provided. Furthermore, as the value of permeability varied so largely in the various classes of ferrous metals, it was impossible to lay down any definite law with respect to the relation of the magnetizing current to the section being tested. The only method of arriving at the correct value to use was reliance on experience and judgment upon the part of the operator. Fortunately, it has been found that operators who are working crack detectors continuously soon become expert in judging the correct value.

Dr. Berthold apparently agrees that d.c. magnetization gives a better degree of penetration than that afforded by the use of alternating current, but his remarks give the impression that with either system the penetration is never very great. I have consistently advocated the use of direct current, and have found by experiment that in most cases the penetration is very nearly uniform throughout the section. I have, for instance, been able to detect flaws at a depth of 3 in. in solid metal, thus showing that the added reluctance caused by the flaws was sufficient to create an extraneous field above it.

In dealing with cracks in iron or steel parts it is advisable to make a study of the types of cracks met with in practice. These generally resolve themselves into three main types: (*a*) the fatigue or strain crack, (*b*) the heat-treatment crack, and (*c*) the grinding crack. Type (*a*) is generally due to overstrain of the part or some bending effect, and usually comes within the province of the user of such part. Such cracks are the easiest to find, as they generally lie in the portion of the part where they may usually be expected; for instance, at a change in the section. They generally lie across the section, and thus the flux should be applied lengthwise for their investigation. Types (*b*) and (*c*) are usually associated with the manufacturing process, and thus their investigation falls upon the maker of the part. Such cracks may be much finer than the strain cracks, and are consequently more difficult to detect. In long bars, either drawn or extruded, the splits are generally radial and frequently extend the length of the whole bar. It is here that the concentric field set up by passing a direct or an alternating current through the bar has been found useful.

Fortunately, most cracks originate at the surface of the metal and are thus easy to find. Certain of the alloy steels in use, however, have been proved to form central cracks or "pipes" in the core. These cracks, being away from the surface, are difficult to find by alternating magnetism, owing to the well-known skin effect.

Dr. Berthold speaks of the disadvantages of d.c. magnets compared with the use of alternating current where demagnetization of the part is concerned; I have never found any serious difficulty here. The use of a potentiometer, with gradual reduction of the magnetizing current in reversed directions, generally affords the necessary degree of neutralization. Where, however, this has been found to take too long, e.g. in mass-production testing, I employ a large electrolytic condenser which is charged up during the magnetizing process. The oscillatory discharge from this condenser is applied to the coil upon switching off, and automatically neutralizes the part. As regards hardened high-carbon steel parts, which are very retentive of residual magnetism, it is very simple to pass these through a ring coil carrying alternating current to neutralize them completely.

One of the greatest troubles I have experienced in connection with the operation of the magnetic method of crack detection is the human element. Where any process of inspection depends upon the vision of the operator, the utmost care must be given to this. In the testing of parts by the mass-production method, where the proportion of faulty parts is relatively low, hours or even days may pass without a single faulty part being found. The monotony of such testing is liable to engender an element of indifference or even carelessness, and thus when the faulty or cracked part does turn up it may be missed. To guard against this state of affairs is often a matter of great difficulty, a fact which indicates that some other method than dependence upon human vision is the next problem for investigation.

The comparison method of magnetically inspecting bar stock, described in the paper by Messrs. Lester, Sanford, and Mochel, is one that the company with which I am

* *Journal I.E.E.*, 1938, vol. 83, p. 491.
† *Philosophical Magazine*, 1937, vol. 23, p. 960.

associated endeavoured to introduce into this country in 1930. Developed by Kinsley, following upon the splendid original work of Burrows and others in the United States, it gave promise of excellent results. Unfortunately, at the time it appeared to be more suited to the laboratory than as a practical method of dealing with steel stock in a commercial works. It also depended upon the use of a mechanical oscillograph, which in itself was far too tricky in operation. Furthermore, the extreme cost of the apparatus militated against its adoption. I am interested to hear that the apparatus has since been developed in a more practical form and that the oscillograph has been replaced by a system of relays and signal lamps. In its original form the apparatus not only indicated the presence of flaws in the rods but also showed by the shapes of the curves on the oscillograph screen any variation in the composition of the metal itself. Some investigations have since been carried out in my company's research department upon a similar process using a cathode-ray tube as the revealer, and these indicate that some reliable system for the commercial testing of bars, strips, and tubes may shortly be available.

**Dr. A. P. M. Fleming** and **Mr. B. G. Churcher** (*in reply*): The apparatus for measuring the thickness of metal plates, described by Prof. Thornton, is of considerable interest and we are glad to note that a paper on it is to be published elsewhere. The principle embodied in the method referred to by Mr. Warren, by means of which the need for a knowledge of the properties of the plate is eliminated, constitutes a valuable advance in technique. As stated, we considered the discussion of methods of measuring dimensions to be outside the scope of a paper on the testing of materials.

Dr. Rayner's remarks on the failure of insulation through thermal instability, a matter briefly referred to on page 522, are of considerable interest, especially in regard to recent work with the aid of the differential analyser.

We note that Mr. Warren disagrees with our preference for utilizing the applied rather than the remanent field in the ferrographic method of crack detection. The probable reason for the disagreement is indicated in Mr. King's contribution to the discussion.

We have not discussed the well-known Doble insulation tester, as our paper primarily covers British practice. While there may be scope for wattmeter methods for limited and particular purposes, such methods are not as sensitive as, or, as Prof. Wales points out, capable of the accuracy of, bridge methods. When, in addition, the great range and flexibility of bridge methods are considered, we do not think that the view that wattmeter methods would lead to results more rapidly obtainable or of wider application will meet with general acceptance. Self-contained portable bridges are available for routine testing, and they can measure all and more than can be obtained with the Doble tester. Metal spraying for the purpose of obtaining good contact with dielectric specimens has been successfully used for ceramics, as stated in the paper, but it is apt to damage the surface of many other materials and has been rejected in favour of other methods for that reason.

Dr. Bailey's remarks on the origin and development of the ferrographic method of crack detection in this country are very welcome. These developments are primarily the outcome of the early work of himself and his associates. Mr. Benson stresses a point raised in the paper, viz. the vital importance of experience in the interpretation of the indications obtained in ferrographic examinations. He also refers to the importance of the correlation of ferrographic and metallurgical observations.

In reply to Mr. Reed, in using the ferrographic method we have observed anomalous indications due to local elastic deformation causing a local variation in permeability, or possibly due to one of the effects mentioned by other speakers, e.g. magnetostrictive or local magnetization effects. It is the possibility of such spurious indications that makes experience in interpretation so essential.

In reply to Mr. Hannah, we have not seen described a method for the continuous magnetic testing of steel strip. However, there would not appear to be any insuperable difficulty in devising one.

Mr. Sulston's experience with regard to electrodes for dielectric testing is in most respects similar to our own.

Prof. Jackson urges the need for more scientific methods for studying the mechanical properties of materials, so that their properties may in due time be expressed in terms of quantities to which it is possible to attach "an exact physical meaning." In our view the difficulties of the subject lie more in the materials themselves than in the experimental methods. With the object of obtaining data on the elastic properties of resilient materials applicable to the prevention of vibration transmission rather than the study of the relation between the constitution of materials and their elastic properties, instruments have been devised which enable the elastic properties under vibratory forces to be measured in clearly-defined physical terms. One such instrument is illustrated in Fig. 18 of our paper, and another form of instrument has been developed in Germany.* While there is not as yet an accepted terminology for the subject, the terms "unit dynamic stiffness" and "damping coefficient" may be used to express the elastic properties and are defined in Ref. (24) of our paper. However, when resilient materials such as cork or rubber are examined experimentally, it is found that they do not behave in the way indicated by simple theory based upon a first-order equation of motion. Thus, for example, the damping coefficient may not be independent of the amplitude of vibration. In other words, it does not appear possible to express the elastic properties of such materials by the few constants indicated by simple theory. We fully agree that this is a wide field for investigation, especially in regard to the relation between constitution and elastic properties.

**Dr. R. Berthold** (*in reply*): In reply to Dr. Bailey I would say that a gentle flow of the magnetic oil over the place where the flaw is situated does not alter my calculations, since these concern the extent and not the greater or lesser clarity of the magnetic image. Dr. Bailey will probably share my view that a powder particle must first be retained over the place where the flaw is, so that it can retain other particles. On page 530 I do not say that "negligible flaws are exaggerated by

* C. Costadini: *Zeitschrift für Technische Physik*, 1936, vol. 17, p. 108.

the use of thin oil," but that fields which are too large have this effect. By "thin" oil, I mean a mixture consisting of a lot of oil and only a little iron powder.

In reply to Mr. King, the results of Figs. 2, 3, and 4, are first of all calculated. Experimental investigations were available for Fig. 3, which was obtained with the aid of plates in layers and of artificial flaws. Other results, in particular those of Fig. 2, were obtained over a period of about a year from the material that came in for testing, and use was also made of etching. The curves in Figs. 2, 3, and 4, are useful, as they permit of a quantitative determination of the relation between the sensitivity of the method and the strength of the magnetic field. I cannot claim, however, that the curves are absolutely accurate, so that I do not wish to contradict the experience of an engineer who says that in practice he has found still finer cracks at still greater depths and with still weaker fields. It would in the first place be desirable, for the control of such capacities, to indicate not the depth but rather the relation of the depth to the thickness of the specimen, as this relation only is conclusive. The unit for the ordinates (induction) of Fig. 5 is gauss/cm$^2$.

I would inform Mr. Stephen that the preparation of the X-ray films is usually carried out by the works engineers, technical assistants, or other works assistants who have been instructed in this work. The results are interpreted by engineers of the State X-Ray Laboratories, or by the railways, or other authorities, who in turn occasionally refer to the State X-Ray Laboratories.

**Mr. V. E. Pullin** (*in reply*): The general discussion illustrates very clearly the importance of the opening remarks in my paper on radiography, to the effect that non-destructive testing as a whole comprises many aspects which must be employed in a complementary manner. I have been particularly interested in the various contributions to the discussion which deal with the magnetic testing of materials, and one cannot fail to be impressed with the increasing appreciation of this method of test. This particular technique has been developed in one form and another for many years in my Directorate in the Research Department at Woolwich, and I am pleased that Mr. Warren of that Department has described some of his work on that subject.

I am interested in Dr. Shearer's remarks. He is, of course, very well qualified to speak of the development of crystal-analysis technique in the industrial research field. At the same time, I am a little disappointed that he has confined his remarks, more or less entirely, to the research aspect of the subject. I cannot help feeling that it would have been interesting if he had told us a little more of the development of certain aspects of this technique to the immediate problems of non-destructive testing, as they present themselves in a works environment rather than that of a laboratory.

I am interested in Dr. Berthold's criticism of my paper, which I accept. At the same time, I am inclined to think that the appreciation of the Schwarzschild exponent does not account entirely for the observed increase of scattered radiation when using salt screens.

In conclusion, I feel very strongly that one of the most important future uses of X-rays in the engineering world will be the examination of welded structures; and in this connection I am at present engaged in further research with the object of evolving a standardized practice as regards both technique and interpretation. Another important sphere for the development of X-ray examination is that of light alloys, especially in aircraft inspection. It is possible for a large amount of this inspection to be carried out on a 100 % basis by visual methods. This development calls for the evolution of special apparatus, embodying specialized mechanical devices for manipulation of the specimen, special high-power high-intensity X-ray tubes, and, in particular, more efficient fluorescent screens.

**Ir. J. E. de Graaf** (*in reply*): The disadvantage of wires, referred to by Mr. Wiltshire, that the sensitivity measured with them varies with their length, is no longer important when the length is sufficiently great, for example 2 in. Wires have, however, the big advantage over stepped penetrameters that they can be used on a piece under inspection, such as a weld, without obscuring any part of it.

The point raised by Mr. Shannon, whether every inch of a weld should be inspected or not, is very important. When a firm starts welding important structures under X-ray inspection it seems necessary to inspect every inch of every weld; but when a staff of trustworthy welders has been formed, it is usually sufficient to inspect only one here and there of the less important welds. For very important welds, e.g. welds in boilers, pipe lines, and the main girders of a bridge, a complete inspection is usually desirable, in view of the possible disastrous consequences of a very faulty weld. It is possible, and in fact is often done, to inspect pipe lines *in situ*, even in narrow conditions. The rays are, as a rule, made to pass the weld to be photographed and the wall of the pipe at the opposite end of the diameter. The place near the film is depicted sharply, but not the opposite wall because of its great distance from the film. Of course the sensitivity is now less than when only one thickness has to be penetrated, but this method is usually the only possible one.

The question put forward by Dr. Desch as to the inner stresses of a material is also very important. It is possible to determine the stresses at the surface of the specimen by means of X-ray crystal analysis. The method has been developed particularly by Glocker* and is tentatively being used for the determination of stresses in structures. Results of laboratory investigations so far are very encouraging, but I do not yet know the results of practical applications.

**Dr. S. F. Dorey** (*in reply*): A considerable proportion of the discussion centres round the subject of magnetic crack detection and the use of X-rays, for both direct and indirect examination of metals. Although these matters are outside the scope of my own paper, I should like to make one or two comments which might be of general interest in regard to non-destructive testing methods.

Dr. Bailey refers to the limitations of the magnetic crack-detection methods, and he points out that as yet there are no reliable methods of non-destructive testing for revealing very small and sub-surface defects in materials. Dr. Förster, on the other hand, claims that by means

* R. Gocker: "Materialprüfung mit Röntgenstrahlen," 1936.

of a search coil of special design he can detect " not only cracks which run perpendicular to the surface, coming out at the surface, but also cracks which are parallel with the surface." Mr. King also speaks with some confidence of the detection of " deep-seated " faults by search-coil methods.

A serious defect which sometimes occurs in a rolled steel plate is an internal lamination. Such defects run parallel with the plate surface and may not reach the plate edges, and so escape visual observation. The necessity for a reliable method for the detection of this type of defect is a matter to which further research might be directed.

The present value of both X-ray and magnetic methods of examination is in the detection of cracks and voids having depth in a direction approximately perpendicular to the surface of the object under test.

Dr. Desch raises the very interesting question as to whether it is possible by any non-destructive method available at present to determine the distribution of internal stresses in masses of metal. Research work is at present being carried out to determine the magnitude and direction of stresses in steel which may result from welding and, in addition to destructive tests, X-ray diffraction methods have been used for the investigation of lattice distortion, presumed to be caused by internal stress. An extensive field exists in industry for non-destructive methods of investigation of stresses in parts of machinery and plant in service, and one of the main impressions left from a study of these papers and the discussion thereon is that more attention might be given to the development of non-destructive testing methods for the detection of faults and peculiarities in material, and for investigation of the causes of defects in machinery.

In regard to my own paper I think it is apparent that much is already being done in the testing of materials for a wide variety of properties in various spheres of industry. Many of the tests referred to in this paper could well form, and indeed have formed, the subject of valuable papers in themselves. Full justice could not of course, be done to them in such a short survey, and it only remains to acknowledge Mr. King's remarks regarding the use of objective noise-meters, and Mr. Heselwood's further elucidation of the " spark test " as a means for checking the chemical analysis of steel.

[The reply of **Messrs. H. H. Lester, R. L. Sanford,** and **N. L. Mochel,** to the discussion will be published later.]

[**Dr. F. Förster** and **Prof. W. Köster** do not wish to submit any reply to the remarks of speakers in the discussion.]

## SOCIÉTÉ FRANÇAISE DES ÉLECTRICIENS

The Société Française des Electriciens is arranging for a series of papers on the subject of Television to be presented in Paris next November during the Société's annual "Discussion Week," and a cordial invitation has been extended to all television engineers in this country to attend the meetings and take part in the discussions.

Any member of The Institution (or non-member) who is desirous of receiving further information from the Société and copies of the papers should notify the Secretary of The Institution (Savoy Place, London, W.C.2), who will then advise the Société accordingly.

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### Passed†

Albuquerque, Robert Francis (*India*).
Baboo, Sriperumbudur Culashekara (*India*).
Bahl, Kidar Nath (*India*).
Bana, Sorabji Dorabji (*India*).
Bellamy, Charles Lang (*South Iran*).
Blakeley, Philip William (*New Zealand*).
Canning, Randall George (*South Africa*).
Carlaw, Arthur Donald (*New Zealand*).
Dissanayake, Sirisena (*Ceylon*).
Dronnikoff, Serge Nicolas (*China*).
Fraser, James Anderson (*New Zealand*).
Gardner, Thomas (*South Iran*).
Gray, Dudley Maurice (*South Africa*).
Greer, Norman Campbell (*Perth, West Australia*).
Gupta, Jagan Nath (*India*).
Hands, Robert Claude (*New Zealand*).
James, Ivor Robert (*India*).
Jog, Balkrishna Laxman (*India*).
Madhavan, V. (*India*).
Magee, James Frederick (*New South Wales*).
Malhotra, Krishan Kumar (*India*).
Marathe, Gopal Mahadeo (*India*).
Mill, Alexander (*New Zealand*).
Mouat, William Neils (*New Zealand*).
Norrish, Goerge Charles William (*Queensland*).
Ochani, Utamsing Gurmukhsing (*India*).
Prasanna, Gorur Roysm Srinivasa (*India*).
Pybus, Jack (*New Zealand*).
Rama Murty, Nelamangala Vuddi Sankara (*India*).
Rao, Guthikonda Virabhadra (*India*).
Rao, Raghunatha Sreenivasa (*India*).
Raymond, Ivan Victor (*India*).
Reddy, S. R. Vithoba (*India*).
Saksena, Virendra Kumar (*India*).
Samuel, Samuel John (*South Africa*).
Seethapathi Rao, Devaguptapu (*India*).
Shah, Shantilal Amarchand (*India*).
Shankaran, Alladi (*India*).
Strachan, Thomas Alexander (*New Zealand*).
Swamy, S. V. Venkatarama (*India*).
Vaidyanathan, N. (*India*).
Wilding, Albert John Foster (*South Africa*).

### Passed Part I only

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Allen, Carrol (*New Zealand*).
Antram, Arthur Burnaby (*South Iran*).
Balasundaram, Narayanaswamy (*India*).
Barraclough, John Francis (*Straits Settlements*).
Bhat, Gurpur Srinivas (*India*).
Broacha, Rustom Hormusji (*India*).
Chandrasinghe, Don Paul (*Ceylon*).
Chappel, Mervyn Joseph William (*South Africa*).
Emms, Arthur George (*New Zealand*).
Hoon, Hari Krishen (*India*).
Houlton, Edgar Moxon (*India*).
Husein, Amir Ebrahim (*India*).
Jenkins, Herbert George (*South Africa*).
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Kaul, Permashwar Nath (*India*).
Kochak, Sharda Shanker (*India*).
Kohli, Shanti Sroup (*India*).
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Muire, Clement Napier (*India*).
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* See page 297.
† This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.


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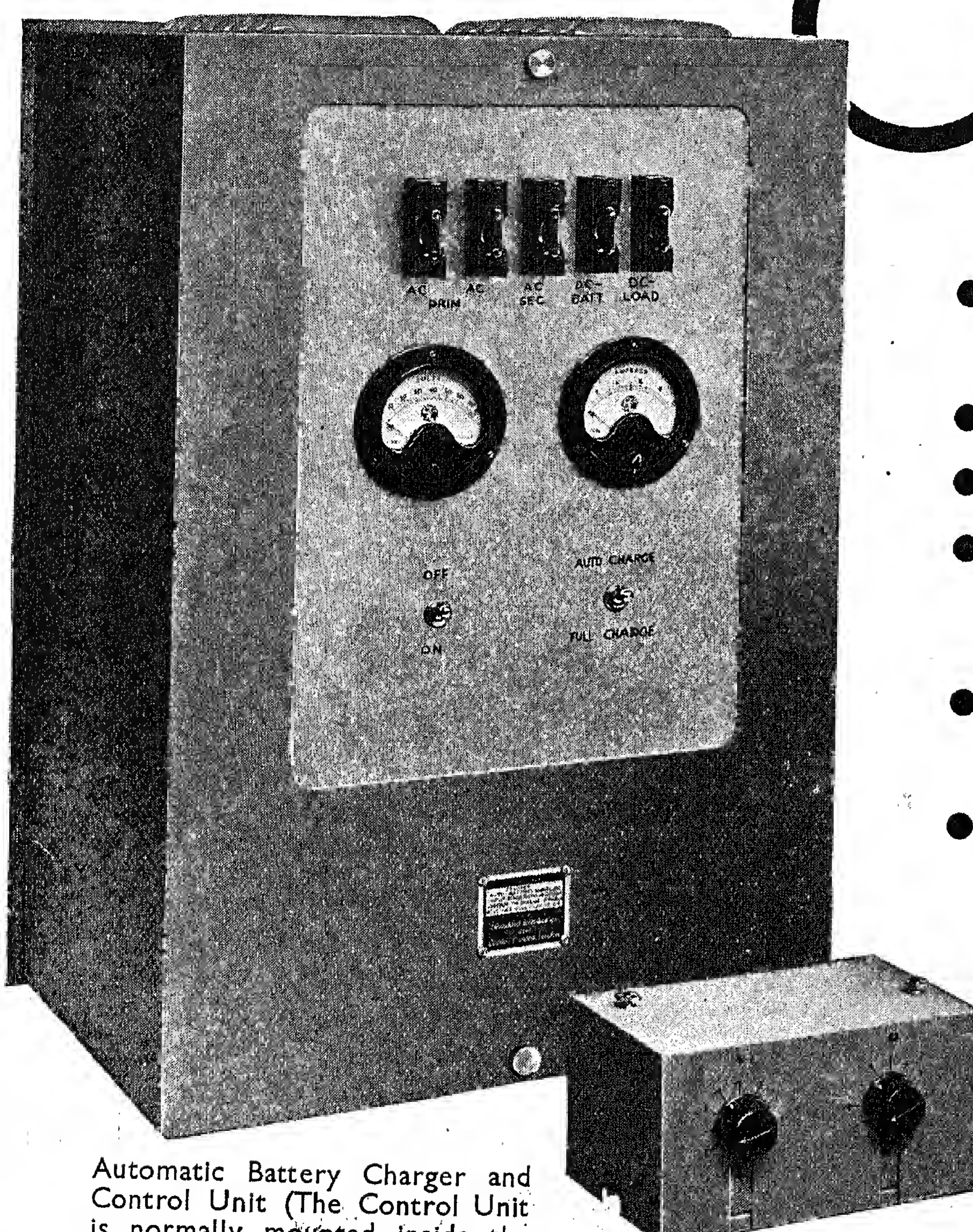


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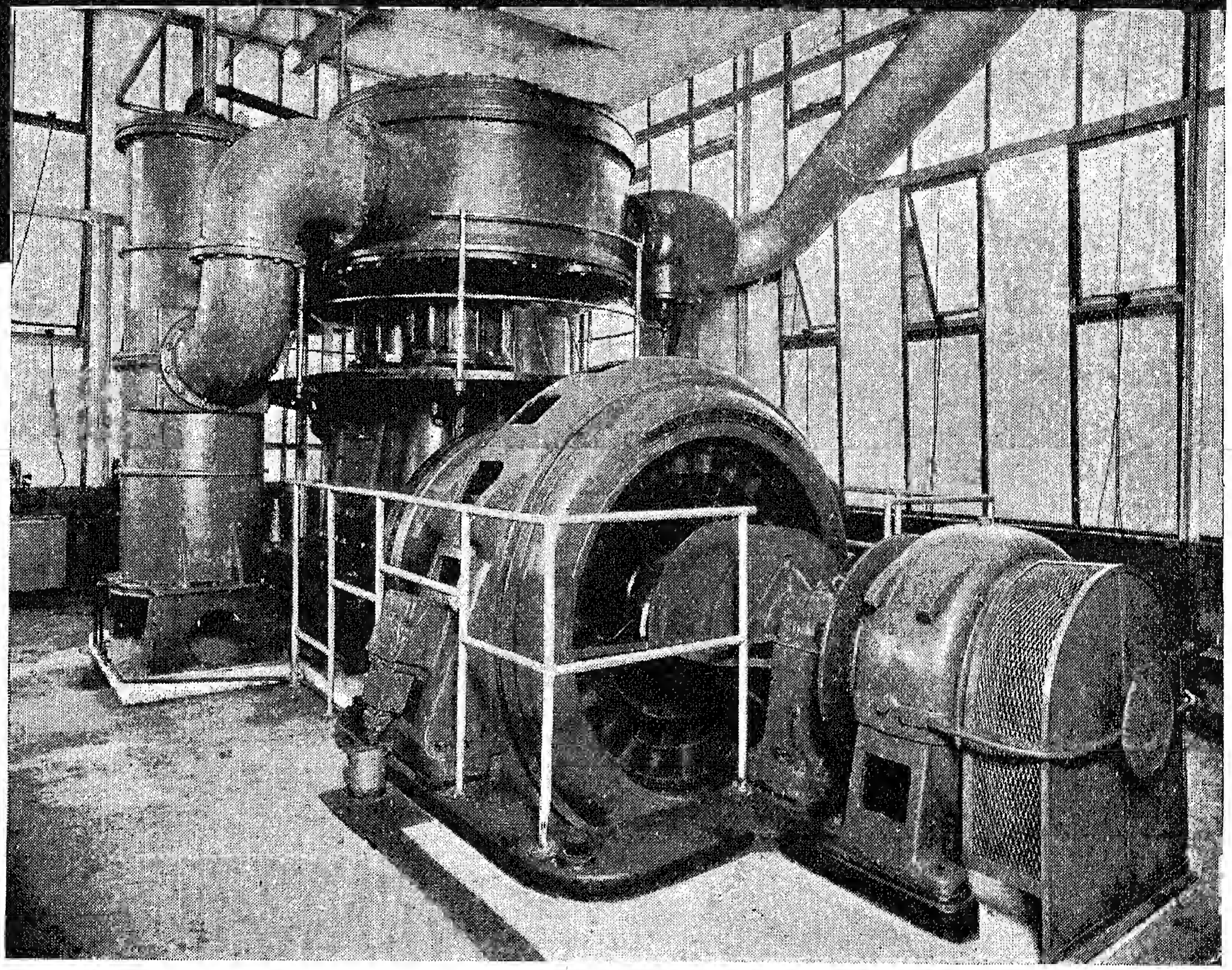

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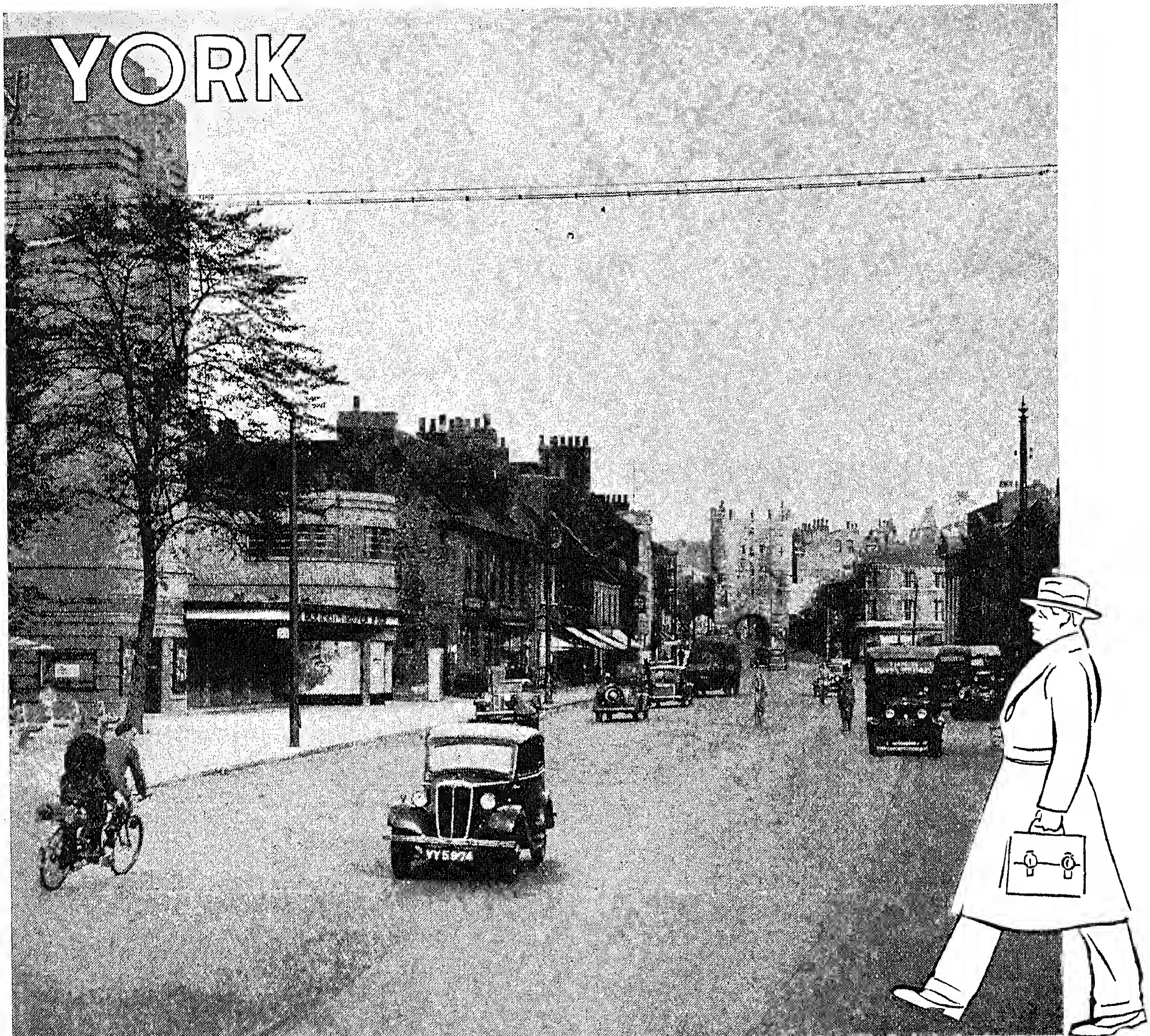
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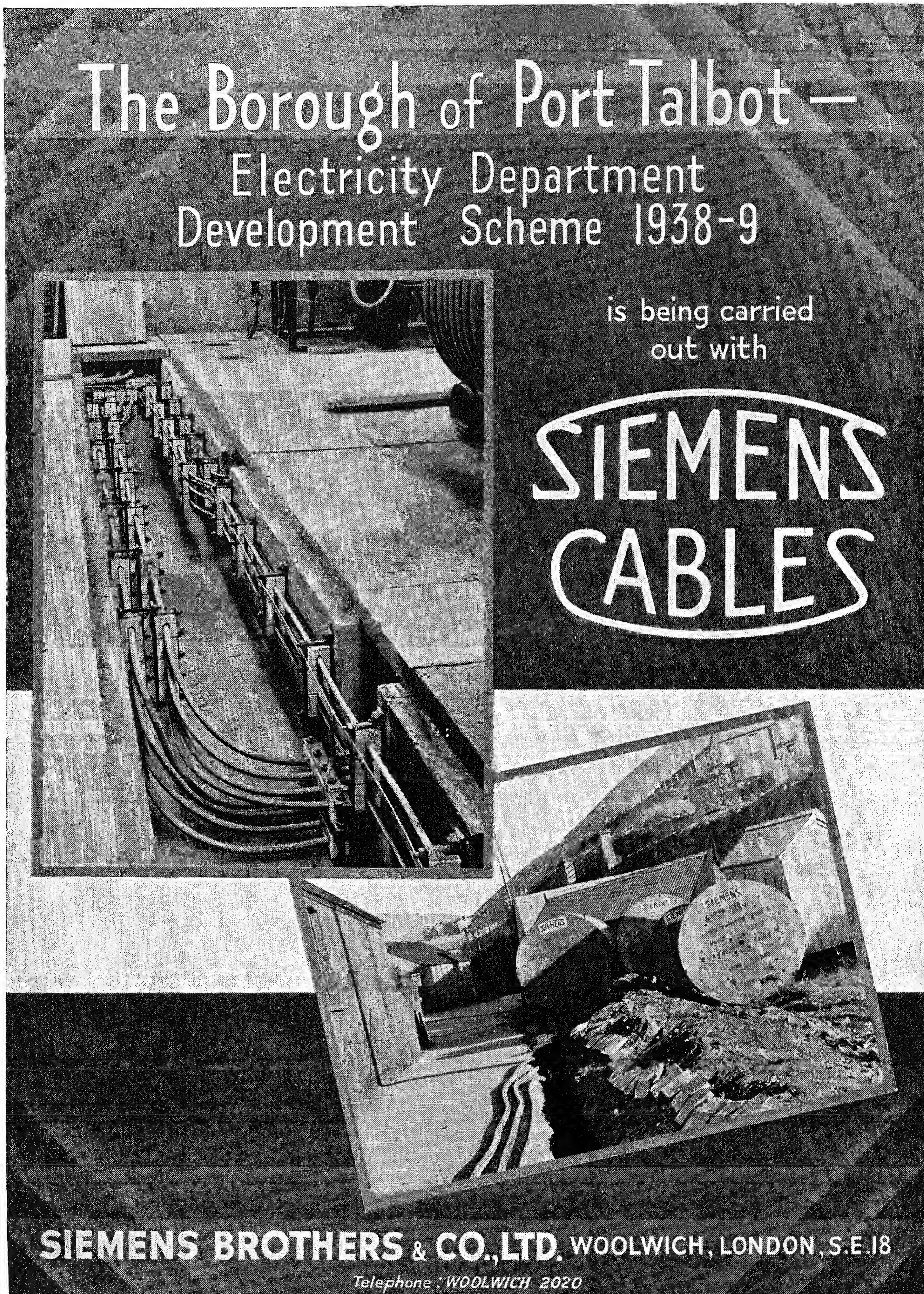
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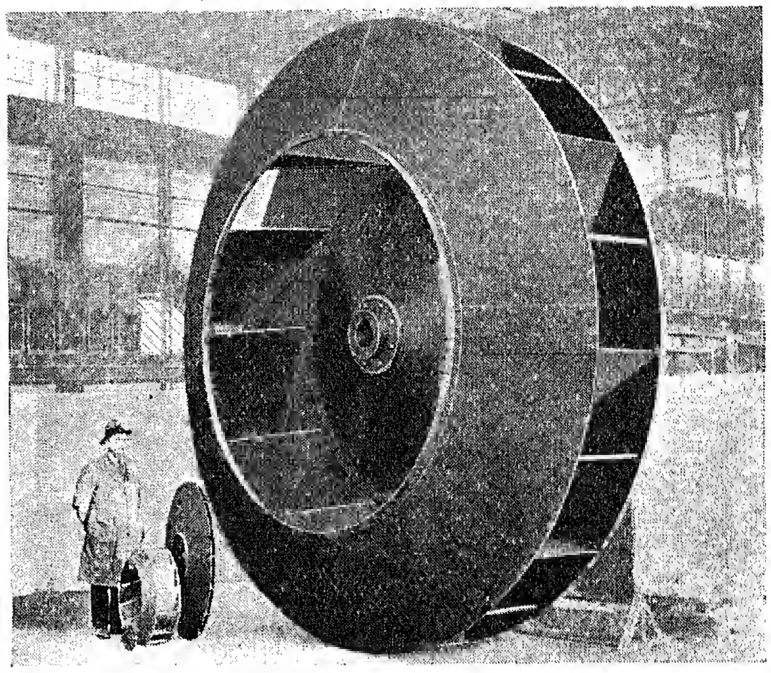

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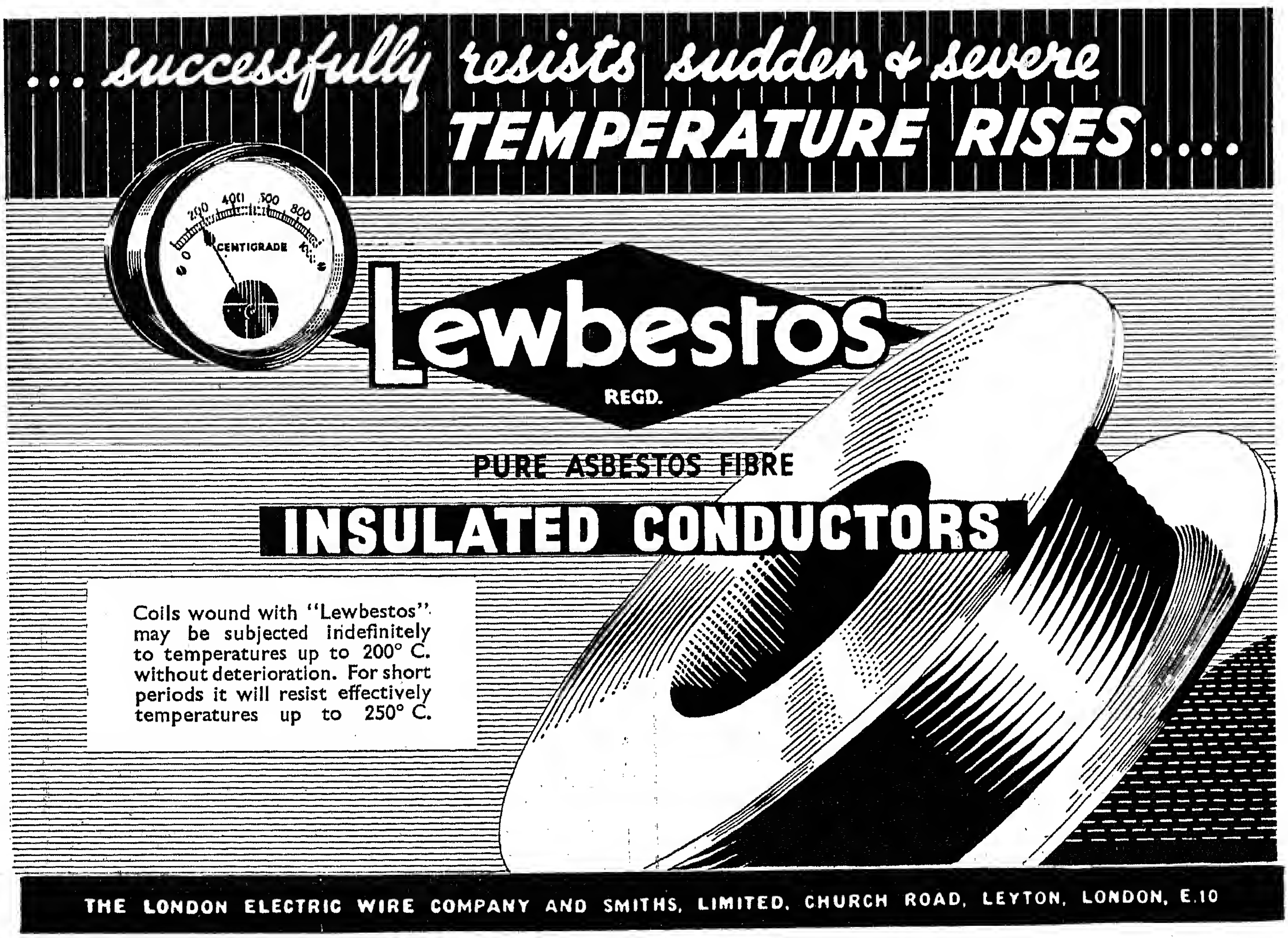

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